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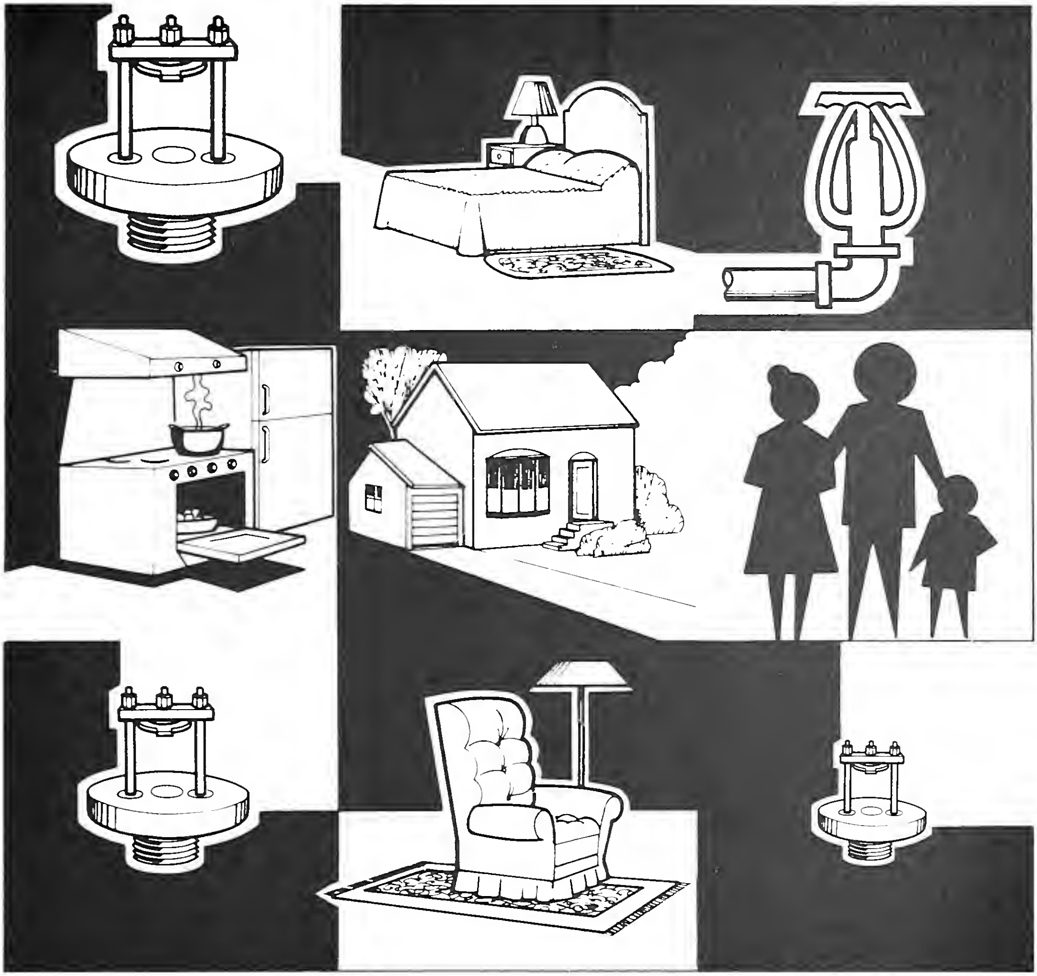

U.S. DEPARTMENT OF COMMERCE

NATIONAL FIRE PREVENTION & CONTROL ADMINISTRATION

NATIONAL FIRE SAFETY & RESEARCH OFFICE

DEVELOPMENT OF LOW-COST RESIDENTIAL SPRINKLER PROTECTION: A TECHNICAL REPORT

DEVELOPMENT OF LOW-COST RESIDENTIAL SPRINKLER PROTECTION: A TECHNICAL REPORT

Prepared for:

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NATIONAL FIRE SAFETY AND RESEARCH OFFICE
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ABSTRACT

A program was undertaken to develop low-cost residential sprinkler systems which require small water discharge rates, yet provide adequate protection for life and property.

The key parameters of the investigation were the water discharge pressure and sprinkler orifice diameter. Seven geometrically similar sprinklers were employed. A total of nine combinations of sprinkler size and water pressure were investigated in realistic living room fires with simulated cigarette ignition. All test combinations provided more than adequate property (structural) protection. For all tests in which reliable carbon monoxide measurements were made, adequate life-safety protection was also provided.

One low-pressure, and one high-pressure combination were selected for future consideration in low-cost systems, both providing conservatively adequate life-safety and property protection in the test fires. The recommended low-pressure combination is a 0.274-in. orifice sprinkler at 8.0 psig (6-gpm discharge rate and 0.04-gpm/ft^2 density) and the high pressure combination, a 0.137-in. orifice sprinkler at 88.5 psig (4.7-gpm discharge rate and 0.032-gpm/ft^2 density). The former discharges water at a rate which is 40 percent of NFPA Standard 13-D.

The water density distribution of a sprinkler has been identified as an important factor in controlling the CO generation rate.

SUMMARY

Loss of life and property due to residential fires can be greatly reduced if a large percentage of residences are equipped with automatic sprinkler systems. However, currently available systems are too costly to be widely installed. In order to improve public acceptance, it is vital to develop low-cost, reliable residential sprinkler systems.

By utilizing water in a more efficient manner, the required water discharge rate can be significantly reduced, which allows for the usage of low-cost plumbing and a limited water supply. Consequently, system costs will be reduced substantially.

OBJECTIVE

The objective of this program has been to develop low-cost reliable residential sprinkler systems which provide adequate protection for life and property. It is expected that the information gained in the program will lead to new performance criteria for approval by recognized laboratories, as well as providing a guide for the installation standard and further development of low-cost systems.

VARIABLES

The key parameters of investigation were the water discharge pressure and sprinkler orifice diameter. Seven geometrically similar sprinklers were employed. A total of nine combinations of sprinkler size and water pressure were investigated, where the sprinkler orifice size varied from 0.438 in. ("1/2-in. standard sprinkler") to 0.110 in., and water pressures of 8.0, 28.5 and 88.5 psig were selected.

EXPERIMENTAL SETUP

The performance of the nine selected combinations was tested in realistic living room fires with simulated cigarette ignition on a couch. All fire tests were conducted in an existing test apartment.

The apartment consists of a 300-sq-ft living-dining area, a 179-sq-ft bedroom, a kitchen, a bathroom, and hallway. The total apartment area is 741 sq ft.

Two pendent experimental sprinklers were installed at the ceiling of the living-dining area (locations are shown in Figure 4), each covering a 150-sq-ft floor area. The experimental sprinklers were set up to be activated by fast-response, commercial sprinkler links. A flowmeter and pressure gages were installed in the sprinkler piping system to measure water discharge rate and water pressure immediately upstream of these sprinklers.

The living room was instrumented to measure a total of 71 channels of data, including: 1) 62 thermocouple measurements; 2) three measurements of the gas flow velocity underneath the ceiling; 3) measurements of CO, CO_2 and O_2 concentrations at eye level; 4) optical density measurements at eye level and 3 in. beneath the ceiling; and 5) a continuous weight measurement of the couch. Of the 62 thermocouples, 42 were employed in 21 pairs to measure the outside and inside surface temperatures of the walls and ceilings at strategic positions. The other 20 thermocouples were installed inside the room to measure gas temperatures.

The 71 data signals were monitored by a data acquisition system with a Hewlett-Packard 2100 S minicomputer.

During the tests, all windows and entrance doors to the apartment were closed. The doors to the bedroom and bathroom were left open.

RESULTS

The fire scenario simulated in the experimental program was a cigarette dropped into the crevice of a couch in the living room, with subsequent initiation of smoldering and eventual transition to flaming. Typically, transition to flaming occurred after a smoldering interval of 60 min. Generation of smoke and CO became vigorous only in the final 15 min. before flaming; however, CO concentrations before flaming never exceeded 360 ppm at eye level. Up to the time flaming occurred, the environment was deemed survivable.

A total of nine combinations of sprinkler size and water pressure were investigated. Survivability was judged from CO concentrations and temperatures

measured at eye level in the living room for a time period extending to 20 min. past sprinkler activation. Structural (property) protection was judged from gas temperature under the ceiling and surface temperatures in the ceiling.

All test combinations of sprinkler size and water pressure provided more than sufficient structural protection. For all tests in which reliable CO measurements were made, adequate life-safety protection was also provided.

The water density distribution of a sprinkler has been identified as an important factor in controlling the generation rate of CO.

RECOMMENDATIONS

One low-pressure and one high-pressure combination were selected for future consideration in low-cost systems, both providing conservatively adequate life-safety and property protection in the test fires. The recommended low pressure combination is a 0.274-in. orifice sprinkler at 8-psig discharge pressure (6-gpm discharge rate; 0.04 gpm/ft^2 density) and the high pressure combination is a 0.137-in. orifice sprinkler at 88.5-psig discharge pressure (4.7-gpm discharge rate; 0.032-gpm/ft^2 density). The former discharges water at a rate which is 40 percent of the NFPA Standard 13-D.

I

INTRODUCTION

Loss of life and property due to residential fires can be greatly reduced, if a large percentage of residences are equipped with automatic sprinkler systems[1]. However, the current design concept for residential sprinkler systems, resulting from relaxation of the industrial-oriented standards, produces a system still too costly to be widely installed. In order to improve system acceptance, it is vital to develop low-cost reliable residential sprinkler systems.

By utilizing water in a more efficient manner, the required water discharge rate in controlling residential fires can be significantly reduced. Low-cost plumbing and a limited water supply would be adequate to handle the smaller water demand. Consequently, system costs could be reduced substantially.

The objective of this program is to develop sprinkler systems which require significantly less water than the current standard[2] (NFPA No. 13-D), but still provide adequate protection for both life and property.

It is expected that the information gained in this program will lead to new performance criteria for approval and listing by recognized laboratories, and will also provide a guide for installation standards and further development of low-cost residential sprinkler systems.

The work described in this report addresses sprinkler performance in residential fires in terms of the sprinkler discharge conditions: discharge rate, water distribution and drop size. The selected discharge conditions have been tested in realistic residential fires.

II

METHOD OF APPROACH

The purpose of a residential sprinkler system is twofold: 1) to assure a survivable environment for a certain period of time sufficient to allow occupants inside the fire room to be rescued or possibly to escape, and 2) to protect property. The survivability can be evaluated from the gas temperature and concentration of toxic gases at eye level in the room of fire origin. Since carbon monoxide alone has been identified as the major cause of fire fatality[3], CO concentration at eye level is employed to judge the survivability of the environment. The adequacy of property protection can be determined from the ceiling temperature above the fire source and gas temperature beneath the ceiling.

Sprinkler performance in residential fires depends not only on sprinkler discharge conditions and the thermal sensitivity of the sprinkler link; in addition, it depends on building geometry, ventilation conditions and fire load. Evaluation of sprinkler performance under various building geometries would be very costly. Therefore, an existing typical apartment was selected as the fire test site.

Since the cause of the majority of fatal residential fires has been attributed to "smoking" in a living room or bedroom,[3] all the fire tests conducted for evaluation of sprinkler discharge conditions have been living room fires started with simulated cigarette ignition. The room geometry, ventilation conditions and fire load were maintained constant.

A series of realistic fire tests have been conducted, varying the sprinkler discharge conditions in a systematic manner. In all the fire tests, CO concentration, gas temperatures and ceiling temperatures were monitored continuously for assessing the adequacy of sprinkler protection to life and property*.

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*"Smokiness", in the sense of visibility, is not judged to be a critical factor in the survivability of a sprinklered fire.

III

EXPERIMENTAL SETUP

3.1 EXPERIMENTAL FACILITY

Figure 1 is a plan view of the test structure relative to an existing fire-test building. The test structure, originally constructed for another program[4] is a type AL Parkersburg Building, constructed of galvanized steel and measuring 24 ft. wide x 44 ft. long x 14 ft. eave height. It contains a 741-sq.-ft. apartment area, a 139-sq.-ft. instrument room, and a 24-ft. long leg of a simulated corridor. The other leg of the simulated corridor extends into the permanent test building and is 34 ft. long. Door A is the entry door to the apartment. Door B provides direct access to the instrument room from the outside.

Figure 2 shows the layout of the one-bedroom apartment. During tests, the entry door (11/16-in. undercut) as well as the door to the instrument room (close fitting) were closed.

Observation windows (wire glass) were provided to view the fires from the instrument room. Wire glass windows to the outside on the north wall were mounted in standard frames provided with the building and were closed in all tests.

The heating/cooling units were located under the windows in the bedroom and living room, shown in Figure 2. These General Electric units* discharge vertically at a rated air flow of 280 cfm. roomside and were operated in an 80 cfm. venting (outside air) mode. The units were operated at either "normal" or "warmer" control setting in tests depending on the pretest room temperature. Exhaust fans mounted in the bathroom and kitchen were always operating during tests. The fans discharged through ducting to the overhead working space. The corridor was pressurized to provide venting flow for the apartment area. For details, see Reference 4.

Figure 3 is an east-west section through the structure. The ceiling height is 8 ft. everywhere. Partitions are 5/8-in. gypsum boards framed in "Unistrut" channels (Unistrut Corp.). An overhead working space, floored with steel grating resting on steel channeling, affords access to ceiling instrumentation. Insulation is indicated in Detail A in Figure 3.

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*Rated 15,700 Btu heating and 12,000 Btu cooling

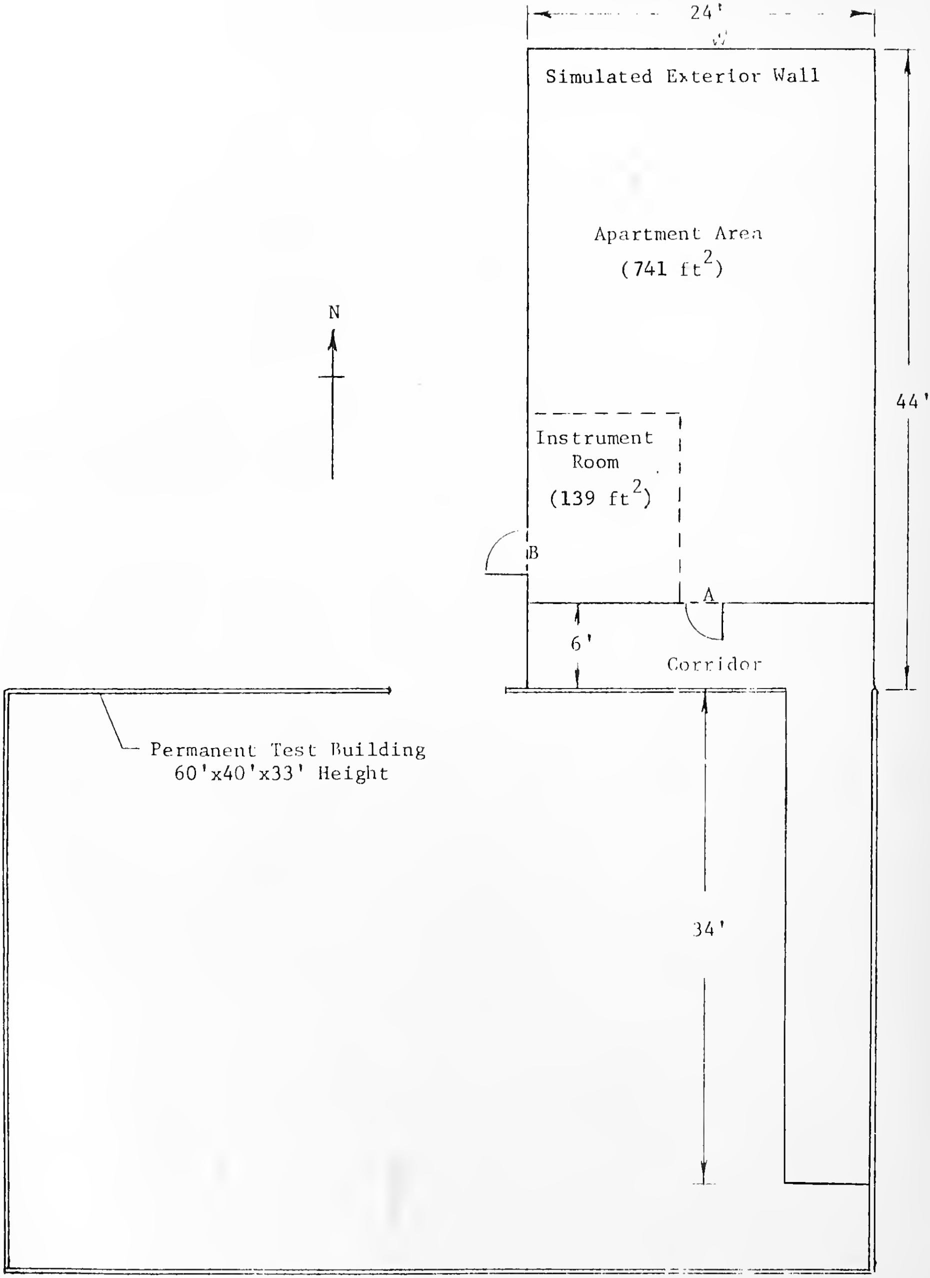

FIGURE 1 TEST STRUCTURE RELATIVE TO EXISTING TEST BUILDING

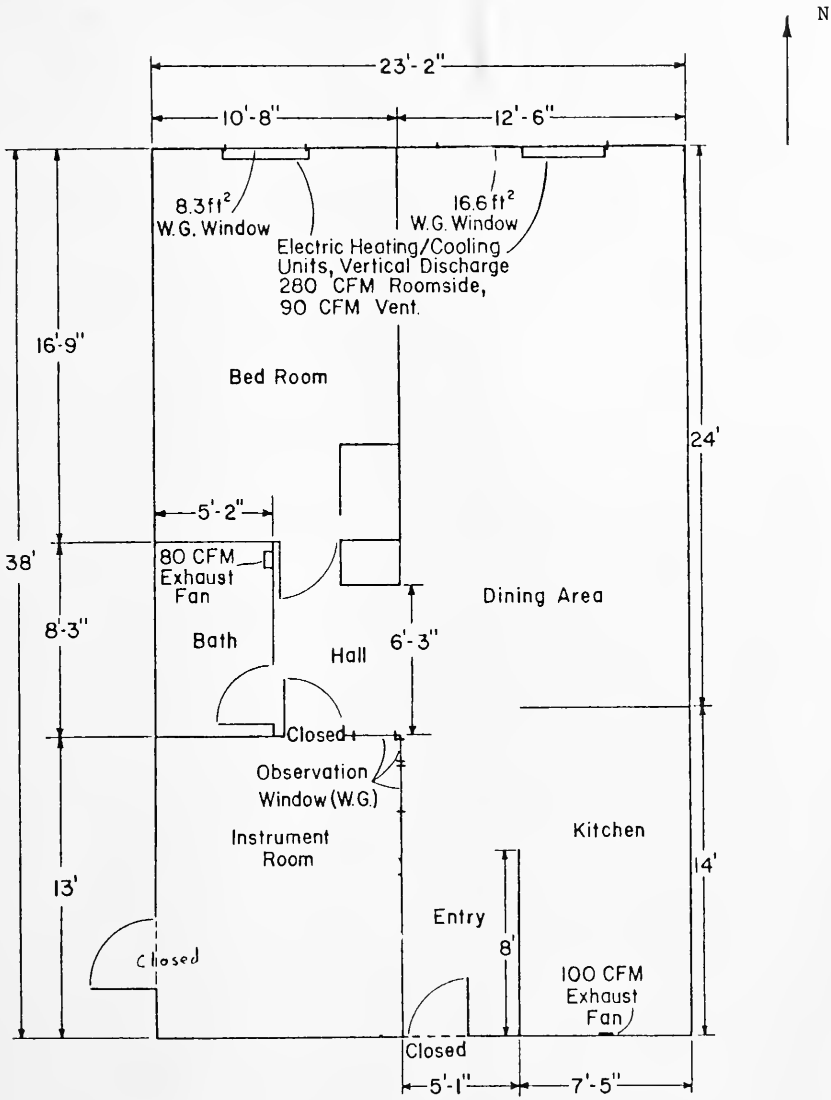

FIGURE 2 TEST APARTMENT FLOOR PLAN

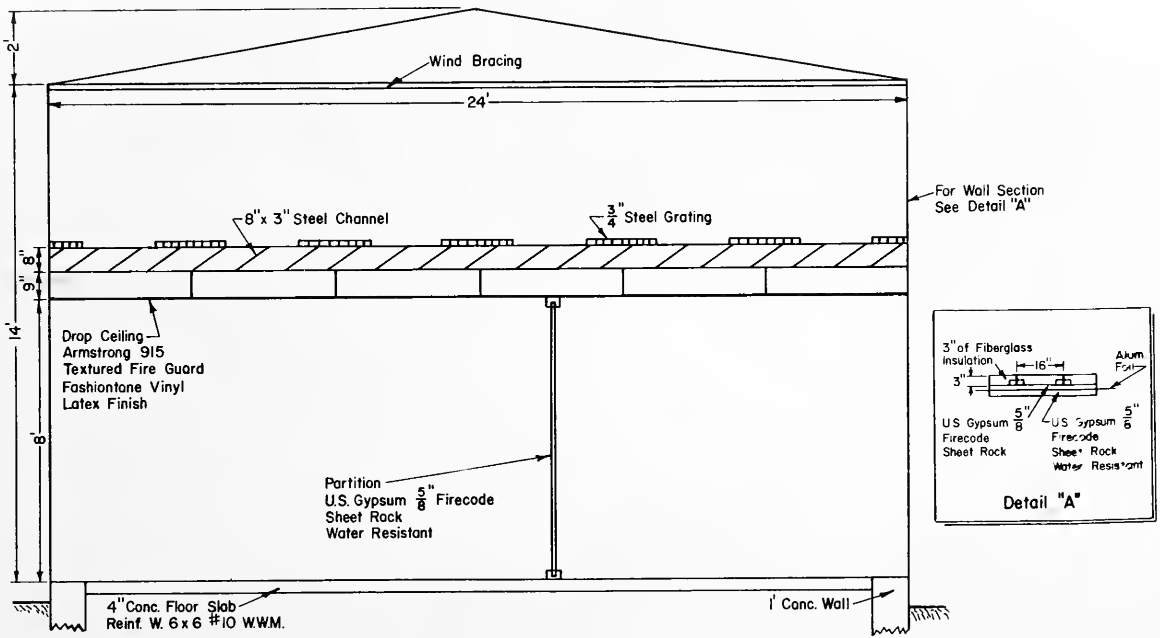

FIGURE 3 EAST-WEST SECTION THROUGH EXPERIMENTAL STRUCTURE

3.2 FURNISHINGS

For each of the 15 tests run in this program, the apartment was furnished with only a couch and room divider placed in the living room as shown in Figures 4 and 5.

The couch was of a sofa lounge design (75-in. x 33-in. x 19-in. high), purchased from a retail store (Sears 1 H 48051N), and consisted of a wooden frame with metal springs, a 5 1/2-in. foam mattress*, and two (36-in. x 8-in. x 12-in. high) urethane foam bolsters (see Figure 6). The covering for the frame, mattress, and bolsters was a cotton and linen blend fabric treated with Scotchgard brand fabric protector. The legs were removed for the tests and the couch supported on a load platform. Two aluminum supports were nailed to the back of the frame to support the bolsters. As shown in Figure 4, the couch was positioned in the north-east corner of the living room, 3 in. from the east wall and 29 in. from the north wall.

The room divider (42 in. x 13 in. x 69 in. high, Signer, Inc. hardwood with veneer finish) was positioned 144 in. from the north wall and 24 in. from the east wall. The primary purpose of the divider was to house the light source and power supplies for the optical density meter. A clock used to show elapsed time during tests was also mounted on the divider.

3.3 SPRINKLERS AND THE WATER SUPPLY SYSTEM

Seven geometrically similar sprinklers were fabricated for the program, based on the proportions of a commercial design (see Figure 7). Sprinklers of the same design were used in a previous study.[5] Figure 8 shows the details of the 0.329-in. orifice diameter sprinkler. The linear scale factors referenced to the largest sprinkler are 1, 3/4, 5/8, 1/2, 3/8, 5/16, and 1/4. These correspond to orifice diameters of 0.438, 0.329, 0.274, 0.219, 0.164, 0.137, and 0.110 in. respectively. Since the volume median drop size distribution generated by geometrically similar sprinklers varies as the 2/3 power of the sprinkler orifice diameter and the -1/3 power of the water pressure, the drop size can be varied in a controllable fashion by systematically changing the sprinkler orifice diameter and water pressure[6]. The key parameters in evaluating the performance of sprinklers in controlling fires are discharge rate, water distribution and drop size.

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*The density of the foam is 1.3 lb/ft^3.

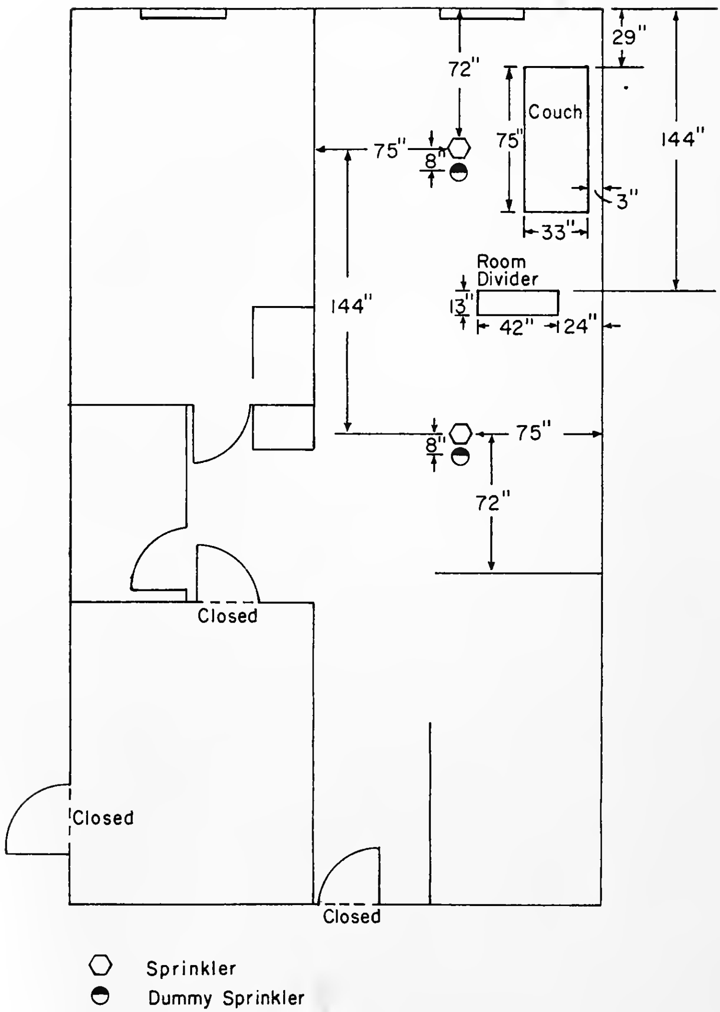


FIGURE 4 LOCATION OF COUCH AND ROOM DIVIDER IN TEST APARTMENT

FIGURE 5 SOFA LOUNGE AND ROOM DIVIDER

FIGURE 6 SOFA LOUNGE

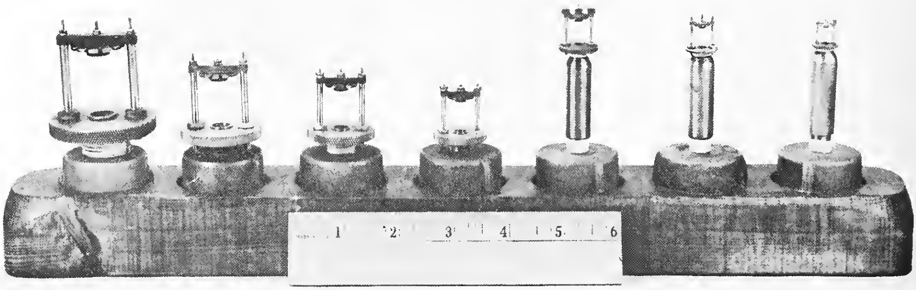


FIGURE 7 THE GEOMETRICALLY SIMILAR SPRINKLERS

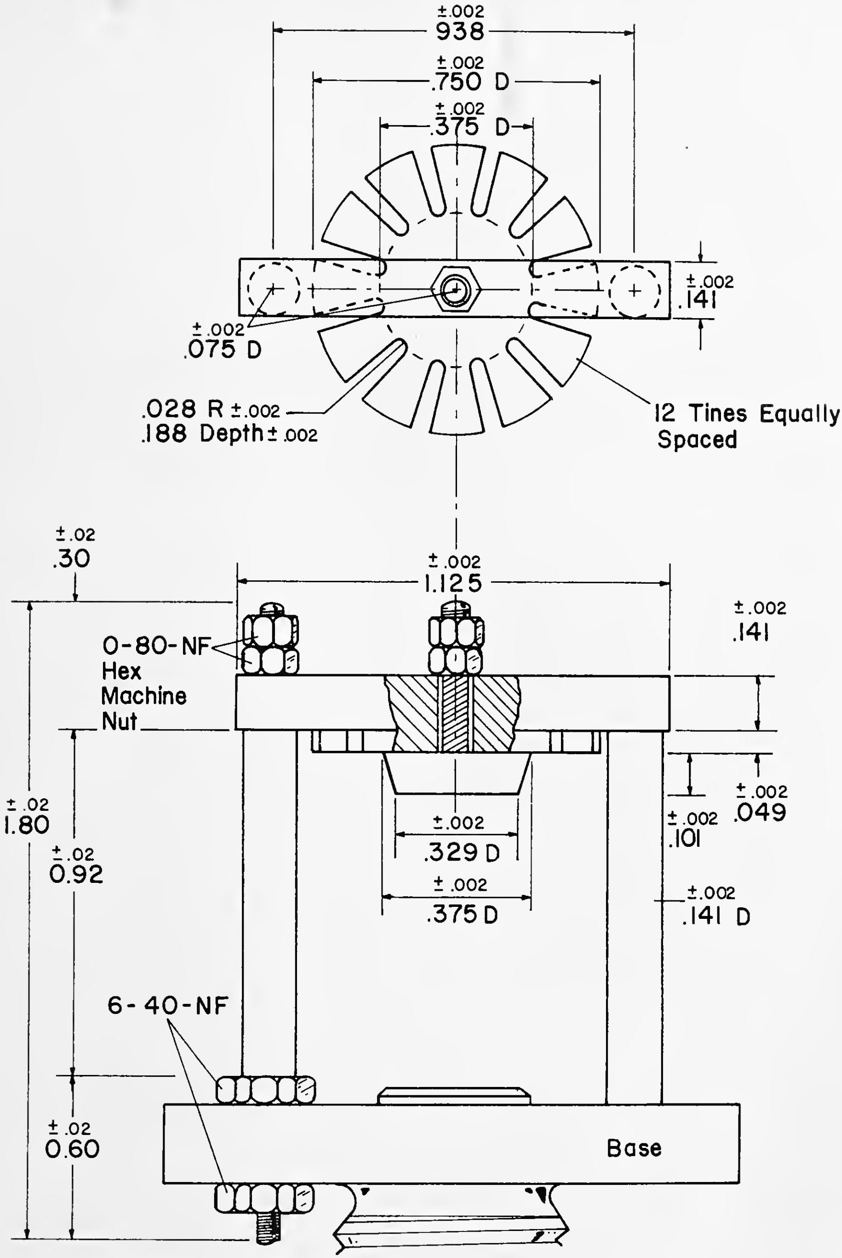


FIGURE 8 DETAILED DIMENSIONS OF THE 3/4-SCALE SPRINKLER.
(a) Deflector and Supporting Rods
(Dimensions in Inches)

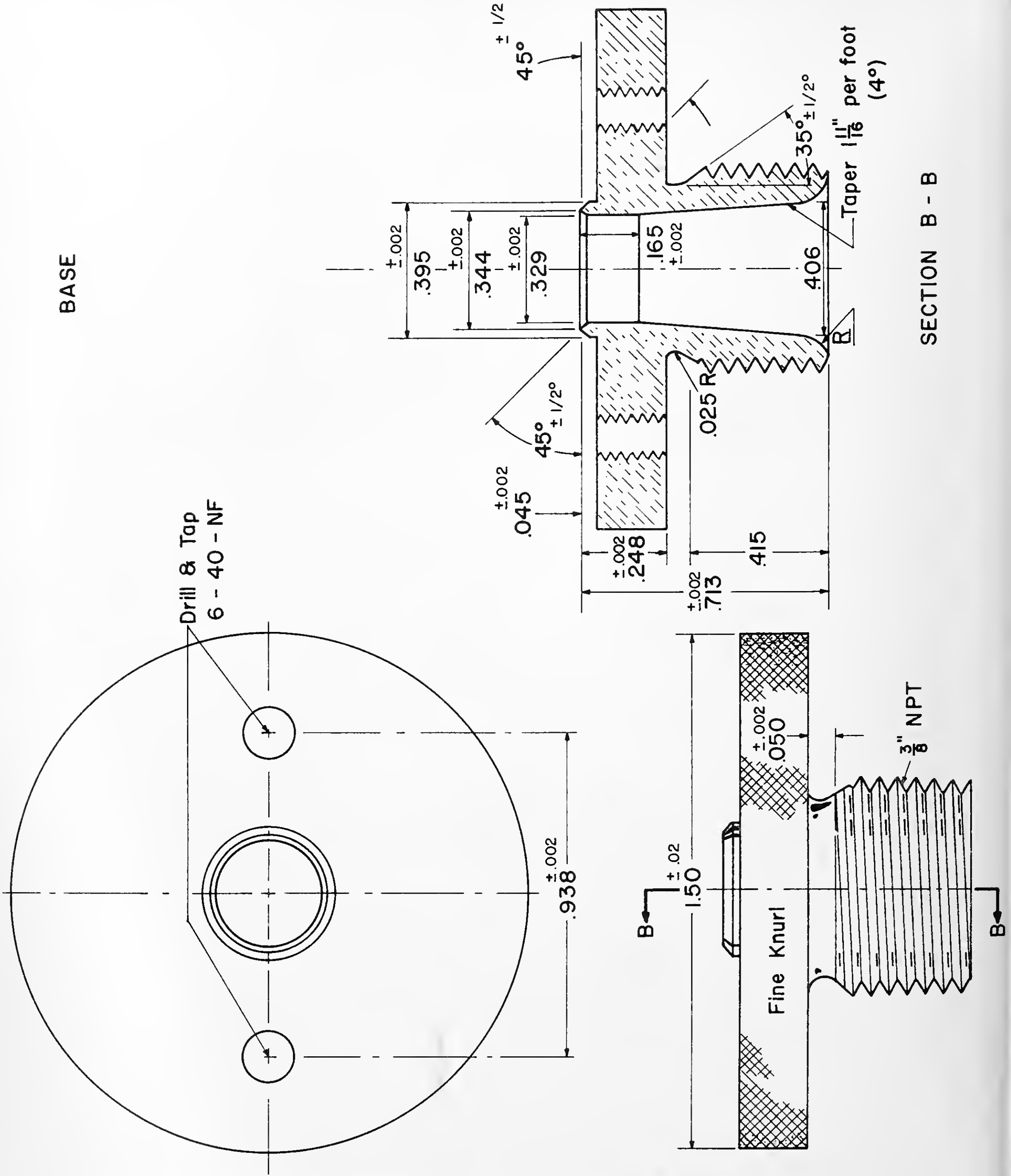


FIGURE 8 DETAILED DIMENSIONS OF THE 3/4-SCALE SPRINKLER (Cont'd.)
(b) Base and Orifice

Two experimental sprinklers were mounted at the ceiling of the living-dining area, each covering a 150-sq-ft. floor area. The distance between the two sprinklers was 12 ft. (see Figure 4). The location of the sprinkler near the north wall was at 6 ft. from the north wall and 6 ft. 3 in. from the east wall. The sprinkler deflector was positioned at 3 in. below the ceiling and the plane of the supporting arms for the deflector was perpendicular to the north wall. A commercial sprinkler with a fast response link was installed 8 in. south of each of the experimental sprinklers. This commercial sprinkler was used to activate water flow to the experimental sprinkler and was not connected to a water supply line. This "dummy" commercial sprinkler was electrically connected to a solenoid valve in the water line for the experimental sprinkler. When the thermal link fused, it acted as an electrical switch opening the solenoid valve and activating the water flow. The link had a temperature rating of 165°F and a time constant near 120 sec* at 5 ft/sec. gas velocity.[7]

Sprinkler discharge pressures (water pressure immediately upstream of the sprinkler) were measured on one of three available Bourdon-type test gages (0-15 psig, 0-30 psig, 0-160 psig). Water was supplied by a pump from a storage tank. All water flow rates were measured using a rotameter (Schutte & Koerting Instruments - full range = 0-25 gpm). Before all tests except the first one, the proper discharge pressure and flow rate were set by opening the solenoid valve and adjusting the flow with a valve located at the rotameter. The solenoid valve was then closed and the pump left running until completion of the tests.

3.4 INSTRUMENTATION

The living room of the test facility was instrumented to measure a total of 71 channels of data, including: 1) 62 thermocouple measurements, 2) three measurements of the gas flow velocity underneath the ceiling, 3) measurements of CO, CO_2 and O_2 concentrations at eye level, 4) optical density measurements, at eye level and 3 in. beneath the ceiling, 5) a continuous weight measurement of the couch.

*Time constants of commercial sprinkler link range from 100 to 250 sec at 5 ft/sec gas velocity.[7]

Figures 9 and 10 show the location of the 62 thermocouples used in the experiments. Of these, 42 were grouped in 21 pairs to measure the inside and outside surface temperatures of the walls (labeled with "W") and ceiling (labeled with "C") at strategic locations. The other 20 thermocouples (labeled "P", "B" and "L") were installed inside the room to measure gas temperatures at various locations and elevations in the room. All thermocouples were made from chromel/alumel 30 gage wire. The wall and ceiling thermocouples were mounted in shallow grooves (1 in. long) filled with high-temperature adhesive such that the thermocouple bead was flush with the surface. These "L" gas temperature thermocouples were supported by Unistrut poles which protected the beads from direct water impingement and were positioned so that the bead extended 1 in. from the pole.

Gas velocities at three locations 3 in. below the ceiling were measured using bidirectional flow probes[8] (Figure 9). The first of these probes (B1) was mounted with the axis of the probe at a 53-degree angle to the north-south direction. The other two were mounted with their axes aligned with the north-south direction. These probes sense and indicate flows in opposite directions with equal sensitivity and are relatively insensitive to flow deviation from axial direction. The probes were hooked to individual electronic manometers (Datametrics Barocel). With this system, it was possible to reliably measure velocities down to 1 ft/sec.

Carbon monoxide, carbon dioxide and oxygen concentrations at eye level (62 in. from the floor) were measured at a single location, 53 in. from the west wall and 160 in. from the north wall using Beckman CO and CO_2 analyzers and a Servomex oxygen analyzer. The gas sample was drawn to the analyzers through 3/8-in. ID (1/2-in. OD) aluminum tubes and 1/4-in. Tygon tubing and then cleaned through a series of glass wool filters, a condenser, and desiccators.

The delay time for the CO and CO_2 measurements was 31 sec. (time constant = 1.69 sec.); for the O_2 measurements, the delay time was 53 sec. (time constant = 2.75 sec.). All data presented in the report have been adjusted for the delays and distortions due to tubing length, filter, condenser, pump and analyzers.[9]

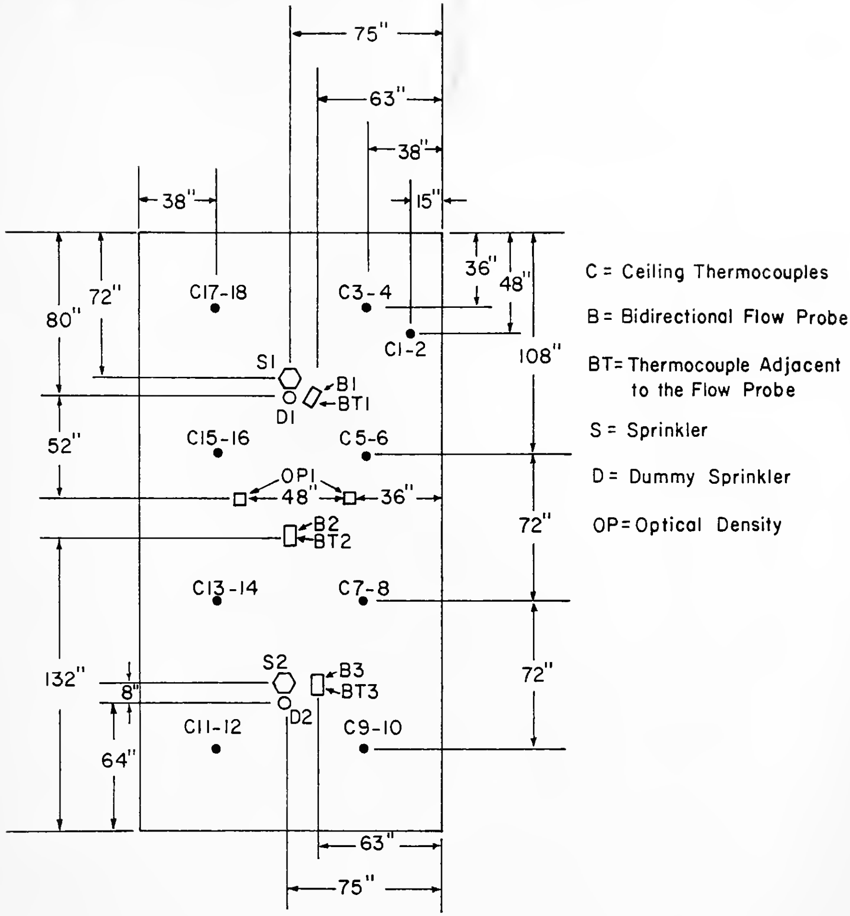
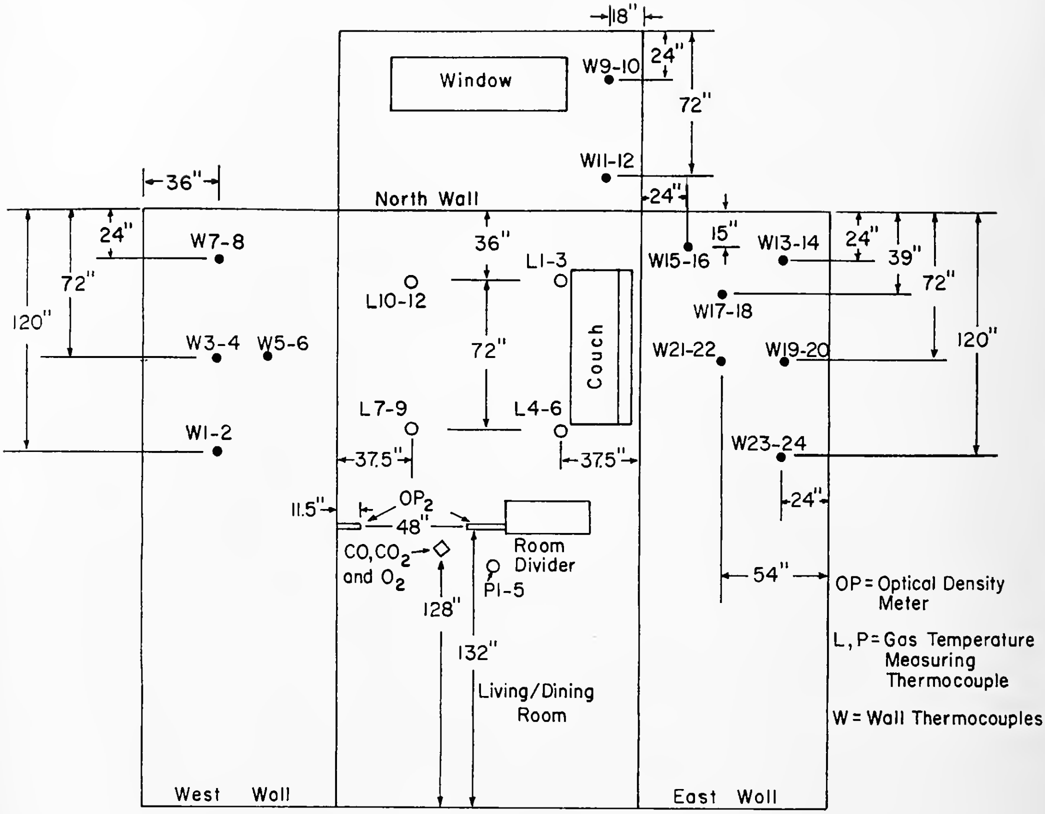


FIGURE 9 LOCATION OF CEILING INSTRUMENTATION (Ceiling Thermocouples, Bidirectional Flow Probes, Ceiling Optical Density Meter, Sprinklers and Dummy Sprinklers) - (All Dimensions in Inches)



L1, 4, 7, 10 - Elev. = 84" P1 - Elev. = 93" P4 - Elev. = 36"

L2, 6, 8, 11 - Elev. = 54" P2 - Elev. = 84" P5 - Elev. = 6"

L3, 6, 9, 12 - Elev. = 18" P3 - Elev. = 66"

FIGURE 10 LOCATION OF WALL THERMOCOUPLES. GAS-TEMPERATURE-MEASURING THERMOCOUPLES. OPTICAL DENSITY METER AND GAS SAMPLING PORT AT EYE LEVEL (All Dimensions in Inches)

A load transducing platform (BLH Electronics, full range = 0-250 lb.) was positioned under the couch to monitor the weight change during the burning process. Before each test, the load platform was centered under the couch. A metal frame the same dimensions as the inside of the couch's wooden frame was placed on the platform for support, and the couch then positioned on the frame.

Two optical density meters, one located at eye level (62 in. from the floor, light beam starting 11 1/2 in. from west wall, 13 ft. from north wall) and the other 3 in. below the ceiling (beam starting 4.5 ft. from west wall, 12 ft. from north wall), were used to measure the degree of smoke obscuration in the living room during the test. For both meters, the unobstructed beam length was 4 ft.

The 71 data signals were monitored by a data acquisition system with a Hewlett Packard 2100 S minicomputer. The system scanned all 71 channels ten times per second, recording the average value each second on a magnetic tape.

Conditions were not severe at locations far away from the fire source. Therefore, only a few critical measurements were selected for data analysis in evaluating life-safety and property protection.

IV

EXPERIMENTAL PROCEDURE AND OBSERVATIONS

4.1 PROCEDURE

During each test, the instrument room and entrance doors were closed as were the doors in the corridor. All the windows were also closed. The doors to the bedroom and bathroom were left open. Air conditioners in the living room and the bedroom were run in the heating mode at a "warmer" control setting for the first five tests and at a "normal" setting for the remaining 10 tests. Fans in the kitchen and bathroom were turned on. The air conditioning package for the corridor was set at 70°F and continuously supplied air to the corridor.

In Test 1, a lighted cigarette was placed under the front edge of the left bolster, 18 in. from the end of the couch to investigate the development of smoldering fires started by cigarette ignition. The cigarette was consumed in approximately 40 min. In the first 40-min. period very little smoke was generated. However, smoldering had been initiated on the couch. At 109 min. 30 sec. from ignition, flaming occurred. At 110 min. 30 sec., the commercial sprinkler link fused and the test was terminated.

The success of initiating smoldering repeatedly and reproducibly by placing a cigarette on the couch could not be guaranteed. Therefore, for the remainder of the test program, a heating coil* (an immersion heater) was used to simulate cigarette ignition. The coil was spread open to 3 in. and placed at the same location as the cigarette in Test 1. The coil was left in place for 30 min. powered at 50 Watts, and then removed from the room. Smoldering on the couch continued for approximately 30 more minutes before transition to flaming occurred. The activation time of the sprinkler near the north wall was in the range of 56 to 130 sec. after flaming. The sprinkler near the hall was never activated by fire.

For all the fire tests except Test 1, the sprinkler was operated for at least 20 min. The water discharge rate was maintained constant and sprinkler-discharge pressure was recorded. After 20 min. of sprinkler operation, the test was terminated.

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*A heater of the kind often used to heat the water in a teacup, rated 300 Watts at 110 v. (KDK, Japan).

4.2 COMPARISON OF THE SMOLDERING FIRES FOR CIGARETTE AND HEATING COIL IGNITION

Figure 11 shows the histories of CO concentrations at eye level for the cigarette-started fire (Test 1) and one of the heating-coil-started fires (Test 11). For the cigarette-started fire, the abscissa has been shifted 45 min. 19 sec. to match the time of sprinkler activation for the two tests. (Very little smoke and CO generation occurred in the first 45 min). For both fires, CO concentrations increased slowly up to 15 min. before flaming and then increased at higher rates, reaching 290 (Test 1) and 310 (Test 11) parts per million at flaming.

Figure 12 shows the histories of the optical density* at eye level for these two tests. Again the abscissa for Test 1 has been shifted. For both tests, the optical density started to increase rapidly approximately 15 min. prior to flaming, reaching 0.26 ft^{-1} (Test 1) and 0.44 ft^{-1} (Test 11) at flaming. (The range of values of optical density at flaming for all the heating-coil-started fires was .23 - .60 ft^{-1}.)

These comparisons indicate that a reasonable simulation of cigarette ignition can be obtained using a heating coil as the ignition source. The heating coil causes the smoldering fire to become established much more quickly than the cigarette but, once established, both fires follow similar histories. For all tests, the smoldering activity started to increase rapidly approximately 15 min before flaming, increasing very rapidly in the last 5 min. The burn patches on the couch just prior to flaming always formed a 1 1/2 to 2-ft diameter semicircular pattern on the mattress of the couch and a 1 to 1 1/2-ft diameter semicircular pattern on the bolster. Smoke generation in the last minutes before flaming was always vigorous, forming a rising smoke plume extending about 3 ft. above the mattress before dispersing throughout the room.

4.3 OBSERVATIONS

Photographs were taken before, during, and after each test. Observations were recorded throughout each test. Samples of the observations and photographs, pertaining to Test 5, are given in Table I and Figure 13.

---

*Optical density per unit length is defined as

$$OD\ (ft^{-1}) = \ell^{-1} \log_{10} (I_o/I)$$

where ℓ is the optical path length (ft^{-1}), I_o and I are the photodetector output (linear with light intensity) in absence and presence of smoke, respectively.

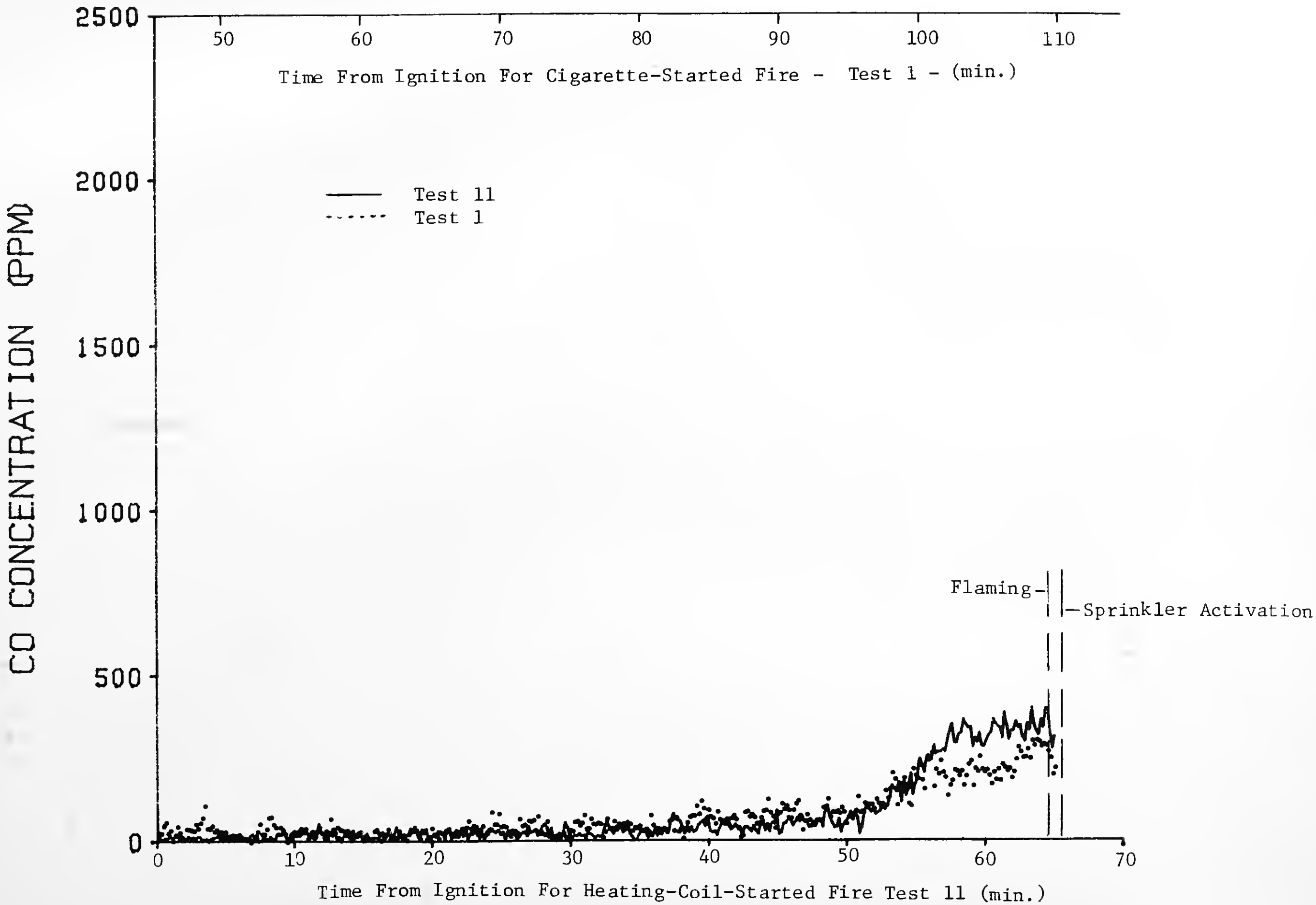


FIGURE 11 COMPARISON OF CO CONCENTRATION AT EYE LEVEL IN LIVING ROOM BEFORE SPRINKLER ACTIVATION FOR CIGARETTE-IGNITION FIRE (Test 1) AND HEATING-COIL-IGNITION FIRE (Test 11) (Location:62-in. Above Floor, 53 in. From West Wall and 13.33 ft. From North Wall)

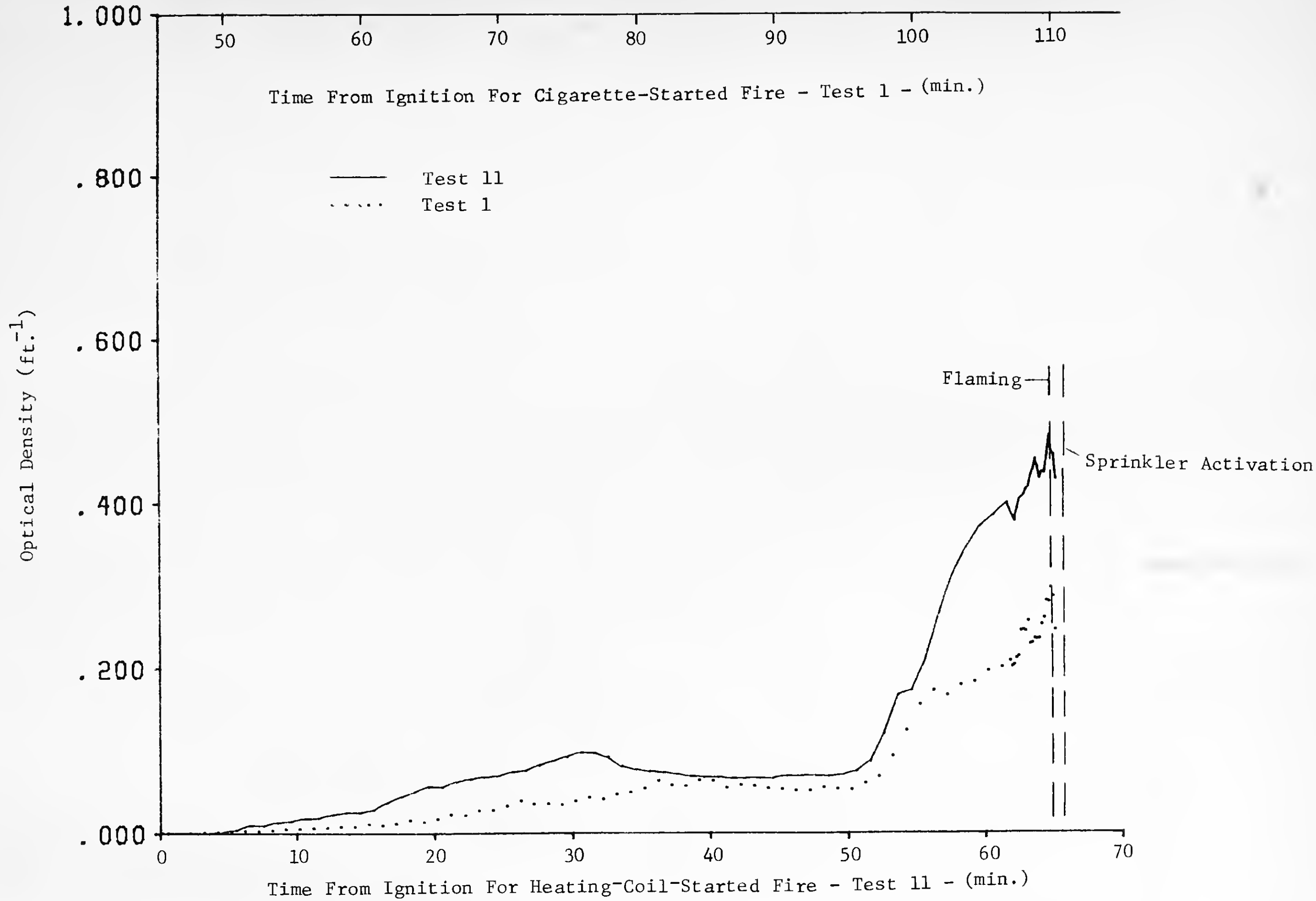


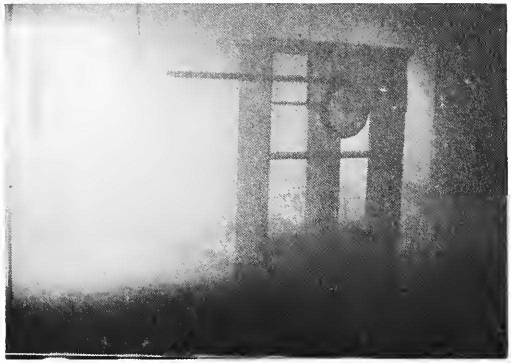
FIGURE 12 COMPARISON OF OPTICAL DENSITY AT EYE LEVEL IN LIVING ROOM BEFORE SPRINKLER ACTIVATION FOR CIGARETTE-IGNITION FIRE (Test 1) AND HEATING-COIL-IGNITION FIRE (Test 11) - (Location: 4-ft. Light Beam, 62-in. Above Floor, and 13 ft. From North Wall)

TABLE I

OBSERVATIONS OF TEST 5

Time From Ignition (min:sec)	Observations
0	Ignition (heating coil at 50 Watt setting)
14:45	Thin smoke layer in area around couch (later extending from ceiling to eye level)
30:00	Burn spot about 6 in. up bolster; moderate to light smoke throughout living room area, smoldering rate still relatively slow, heating coil removed
40:00	Still good visibility in room (moderate to light smoke cloud); burn patch has spread to the side but not vertically (1 1/2 - 2 ft. wide burn patch)
55:00	Smoldering rate has increased; visibility still good (moderately dense smoke cloud throughout room)
60:00	Burn patch on bolster 6 in. up side and about 1 - 1 1/2 ft. wide; burn patch on mattress semicircular; approximately 1 1/2 - 2 ft. in diameter and extending under bolster; smoldering rate increasing; smoke buildup becoming heavy
62:00	Smoldering rate increasing; smoke buildup increasing; visibility becoming poor
65:00	Couch barely visible from control room
68:16	Flaming, flames rising 3 ft. vertically, flames confined to burn patch area; left bolster being consumed
69:35	Sprinkler activation - flames put out; sprinkler spray distributed smoke through the entire room
Post Test	Left bolster badly burned; 2-ft. semicircle burned in mattress; small patch on box springs burned

a) 10 Min After Ignition



b) 30 Min After Ignition

c) 57 Min After Ignition

FIGURE 13 PICTORIAL HISTORY OF THE FIRE

d) Flaming

e) 1 Min After Flaming

V

SUMMARY OF TESTS

Table II summarizes the test conditions of the 15 tests, which represent nine combinations of water-discharge pressures and sprinkler-orifice diameters. Due to problems with instrumentation or the data acquisition system, some of the tests were repeated. The repeat tests offer some check on the reproducibility of the test data.

In Test 13, a damaged couch, used in a test which was quickly terminated because of premature sprinkler activation, was used. Moisture in the couch from the aborted test significantly slowed the smoldering process which made it difficult to compare the data from this test with those from the other tests. This test was, therefore, not used in the data analysis.

TABLE II

SUMMARY OF NFPCA RESIDENTIAL SPRINKLER TESTS

Test No.	Water Pressure (psig)	Sprinkler Orifice Dia. (in.)	Water Discharge Rate (gal/min)	Ignition Source	Control Setting of Air Conditioners Inside Apartment	Comment
1	-	-	-	cigarette	warmer	
2	8.0	0.438	15.0	heating coil	"	gas velocities not measured
3	8.0	0.329	8.8	" "	"	
4	8.0	0.274	6.0	" "	"	
5	28.5	0.219	7.0	" "	"	data mag. system malfunctioned
6	8.0	0.438	15.0	" "	normal	leakage in the gas sampling line, CO measurement not reliable
7	88.5	0.110	3.4	" "	"	"
8	88.5	0.137	4.7	" "	"	"
9	28.5	0.164	3.9	" "	"	"
10	28.5	0.219	7.0	" "	"	
11	8.0	0.438	15.0	" "	"	
12	28.5	0.274	11.5	" "	"	
13	28.5	0.164	3.9	" "	"	damaged couch was used
14	88.5	0.164	6.7	" "	"	
15	88.5	0.137	4.7	" "	"	

VI

RESULTS

Three sprinkler-discharge pressures were employed in the test series: 8, 28.5 and 88.5 psig. For each discharge pressure, three different sprinkler sizes were employed, corresponding to three different discharge rates. Table III lists the discharge rate, application density*, K Factor** and relative drop size, for the sprinkler discharge conditions tested. The 0.438-in. sprinkler operating at a 0.1 gpm/ft.^{2} density complies with the NFPA 13-D standard for installation of sprinkler systems in one- and two-family dwellings.

Geometrically similar sprinklers were employed, for which the relative volume median drop size varies as the -1/3 power of the water pressure and 2/3 power of the orifice diameter. Hence, the variations in water pressure and sprinkler size correspond to predictable variations in relative drop size. The predicted values of relative drop size are included in the Table.

The approximate <u>local</u> application density over the surface area of the mattress of the couch is also presented in Table III. For measurement details, see Section 6.3.

Among the 15 tests conducted, data from the nine satisfactory tests (see Table II) are presented in the following subsections to evaluate the performance of the various sprinkler discharge conditions. These nine are Tests 11, 3, 4 for 8 psig; Tests 12, 10, 9 for 28.5 psig; and Tests 14, 15, 7 for 88.5 psig. See Table II for identification of the test numbers with the associated sprinkler discharge conditions.

6.1 LIFE-SAFETY PROTECTION

The adequacy of life-safety protection provided by sprinklers can best be evaluated from measurements of CO concentration and gas temperature at eye level in the room of fire origin.

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* Application density is discharge rate divided by the coverage area, which is 150 sq ft for these tests.

**K factor, a number to indicate the sprinkler discharge capacity, is defined as the discharge rate, W, divided by the square root of the discharge pressure, Δp, i.e., $K = W\ (gpm)/[\Delta p\ (psig)]^{0.5}$

TABLE III

SPRINKLER DISCHARGE VARIABLES

Sprinkler Discharge Pressure Δp (psig)		Sprinkler Orifice Diamater, D (in.)						
		0.438	0.329	0.274	0.219	0.164	0.137	0.110
8	Water Discharge Rate W (gpm)	15.0	8.8	6.0				
	Application Density (gpm/ft^2)	0.100	0.059	0.040				
	Local Application Density on Couch (gpm/ft^2)	0.081	0.044	0.036				
	K Factor	5.30	3.11	2.12				
	Relative Drop Size, d	1	0.826	0.731				
28.5	Water Discharge Rate W (gpm)			11.5	7.0	3.9		
	Application Density (gpm/ft^2)			0.077	0.047	0.026		
	Local Application Density on Couch (gpm/ft^2)			0.051	0.033	0.015		
	K Factor			2.15	1.31	0.731		
	Relative Drop Size, d			0.479	0.412	0.340		
88.5	Water Discharge Rate W (gpm)					6.8	4.7	3.4
	Application Density (gpm/ft^2)					0.045	0.031	0.023
	Local Application Density on Couch (gpm/ft^2)					0.037	0.028	0.007
	K Factor					0.723	0.500	0.361
	Relative Drop Size, d					0.233	0.207	0.179

Note: Relative Drop Size, $d = (\Delta p/\Delta p_o)^{-1/3} (D/D_o)^{2/3}$

$\Delta p_o = 8.0$ psig

$D_o = 0.438$ in.

K Factor $= W/\sqrt{\Delta p}$

Carbon monoxide exerts its primary toxic effect by reducing the oxygen-carrying capacity of the blood. Once CO enters the body, it combines reversibly with the chief oxygen-carrying protein of the red blood cells, hemoglobin. This complex of CO and hemoglobin is termed "carboxyhemoglobin" (CO Hb), a 16-20 percent CO Hb saturation in venous blood will cause headache and an "abnormal visual evoked response"[10]. The amount of CO Hb formation depends on concentration and exposure duration. It is estimated[10] that a 43-min. exposure at 1000 ppm, a 100-min. exposure at 500 ppm, or a 400-min. exposure at 200 ppm will result in a 20 percent CO Hb saturation in blood. The integrated values of CO concentration over the corresponding exposure period for each of these conditions is at least 43,000 ppm-min. This integrated value, 43,000 ppm-min, has been used as the criterion for evaluating the CO hazard in this test program.

Estimates of "hazardous levels" reported by Yuill[11] are 3000 ppm for "minutes", 1,600 ppm for 1/2 hour, 800 ppm for 1-2 hours, and 120 ppm for 8 hours. The integrated value of CO concentration over the associated time period for these data is approximately 48,000 ppm-min. which is consistent with the proposed critical value (43,000 ppm-min).

Table IV presents the CO concentration at eye level near the center of the living-dining area. At the commencement of flaming, CO concentration was in the range of 300-360 ppm. For the three discharge conditions: 1) 0.438-in. sprinkler at 8 psig (15 gpm), 2) 0.329-in. sprinkler at 8 psig (8.8 gpm), and 3) 0.164-in. sprinkler at 88.5 psig (6.9 gpm), the CO concentrations were maintained below 450 ppm during the entire test period, as shown in Table IV and Figure 14.

For the rest of the tests, CO concentration increased during sprinkler operation but at <u>much smaller rates</u> than those of typical room fires[12,13] without sprinkler protection. The maximum values of CO concentration range from 1630 to 2500 ppm as shown in Figure 15. For two of the sprinkler-discharge conditions (0.164-in. sprinkler at 28.5 psig and 0.110-in. sprinkler at 88.5 psig), CO measurements were not performed correctly and have, therefore, not been reported.

TABLE IV

CO CONCENTRATION AT EYE LEVEL, (ppm)

Sprinkler Discharge Pressure Δp(psig)		Sprinkler Orifice Diamater, D (in.)						
		0.438	0.329	0.274	0.219	0.164	0.137	0.110
	CO at t_f	360	320	330				
	CO at t_s	320	240	250				
8	CO at t_s + 5 min	230	320	570				
	CO at t_s + 10 min	150	250	1180				
	CO at t_s + 20 min	110	230	1440				
	CO at t_f			340	310	-		
	CO at t_s			110	210	-		
28.5	CO at t_s + 5 min			1400	750	-		
	CO at t_s + 10 min			2130	1650	-		
	CO at t_s + 20 min			2010	1850	-		
	CO at t_f					330	300	-
	CO at t_s					280	280	-
88.5	CO at t_s + 5 min					335	740	-
	CO at t_s + 10 min					420	1320	-
	CO at t_s + 20 min					370	1730	

Note: t_f - time of flaming from ignition

t_s - time of sprinkler activation from ignition

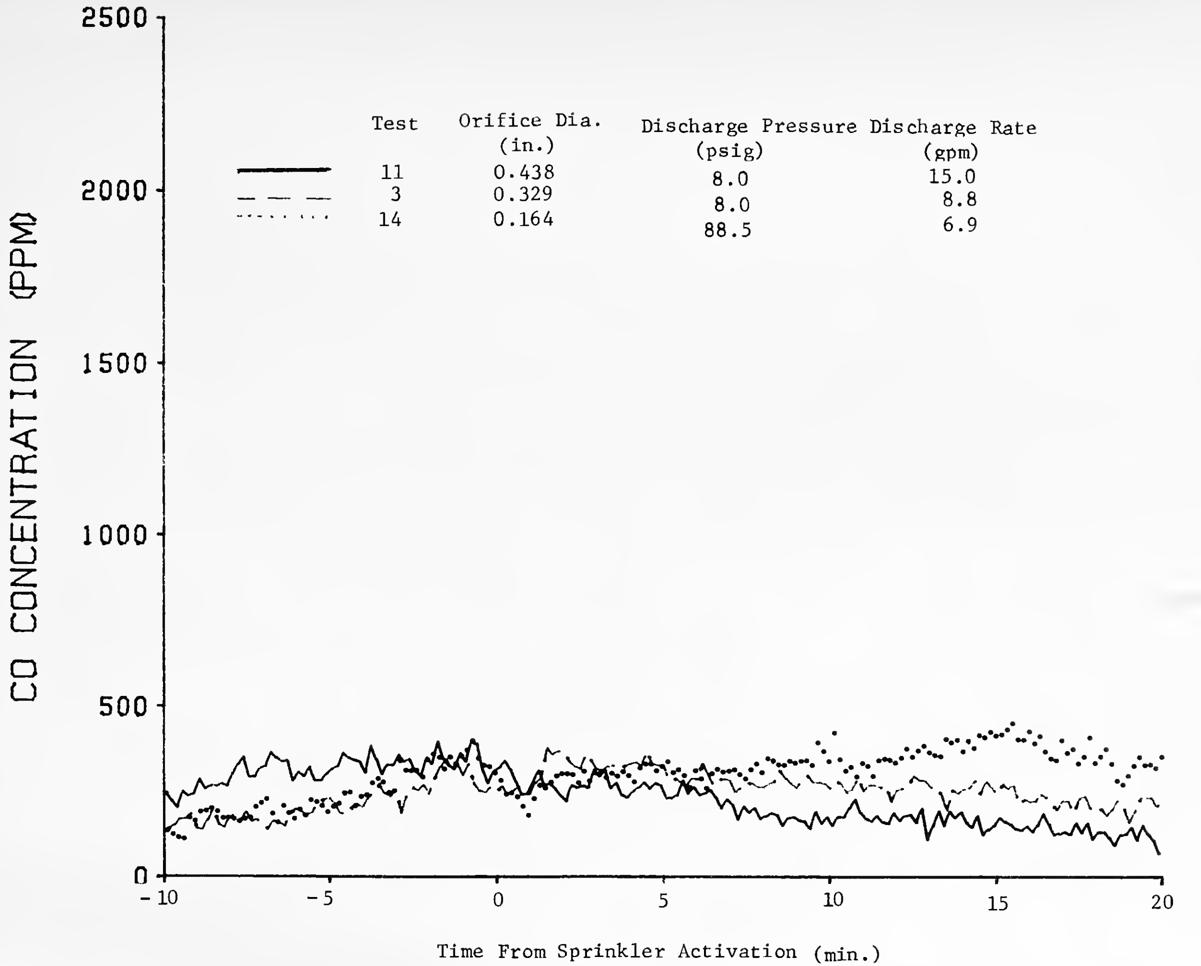


FIGURE 14 CO CONCENTRATION AT EYE LEVEL IN LIVING ROOM FOR TESTS 3, 11, AND 14

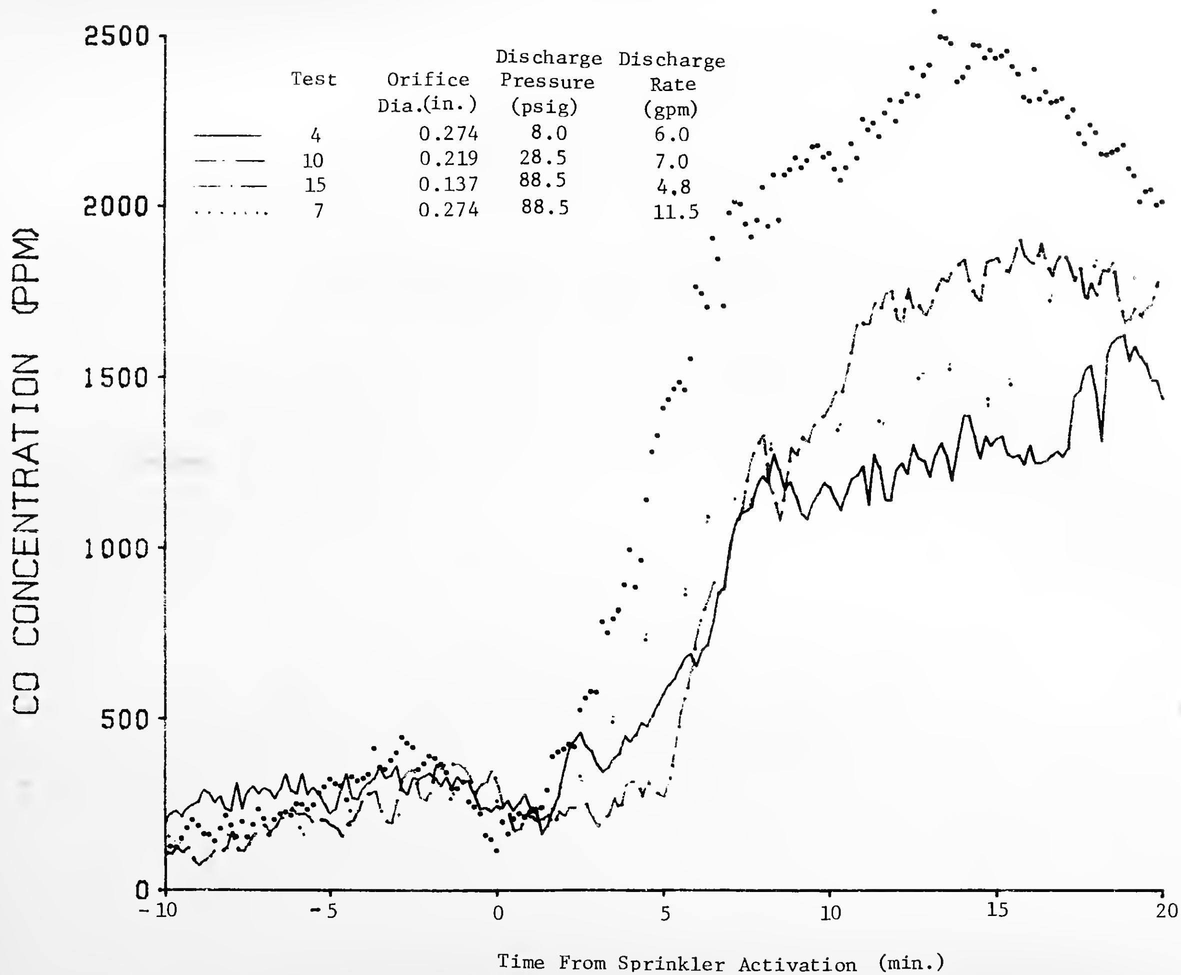


FIGURE 15 CO CONCENTRATION AT EYE LEVEL IN LIVING ROOM FOR TESTS 4, 7, 10, AND 15

The cumulative CO concentration (ppm-min) are shown in Table V, at 5, 10 and 20 min after sprinkler activation. For all the tests with reliable measurements, the cumulative CO concentrations at the end of the test (20 min after sprinkler activation) were less than 40,000 ppm-min. which is below the estimated critical integrated value (43,000 ppm-min). For the lowest water discharge pressure (8 psig), the 0.274-in. sprinkler discharging 6 gpm kept the cumulative CO concentration below 28,000 ppm-min. until the end of the test, 33 percent below the estimated critical value.

The gas temperature at eye level at the time of sprinkler activation and 1 min. after sprinkler activation is listed in Table VI. This temperature was measured at 54 in. from the floor, 36 in. from the east and the north walls, approximately 2.5 ft from the flame axis. At the time of sprinkler activation, its value was in the range of 131-159°F.

The gas temperature dropped sharply after sprinkler operation. At 1 min. after sprinkler activation, the gas temperature at eye level was below 92°F for all the tests as shown in Table VI. The hazardous levels for heat exposure reported by Yuill[11] are 212°F for 1/2 hour, 150°F for 1-2 hours and 120°F for 8 hours. Therefore, for all the sprinkler conditions tested, the danger of overexposure to heat was very slight.

A residential sprinkler protection system is intended to maintain a survivable environment of the fire room for a limited period of time, sufficient for occupants to be rescued (or possibly to escape). A period of 20 min. after sprinkler operation appears reasonable. Based on the consideration of life-safety protection, judged from the CO concentration and gas temperature measurements at eye level, the following two sprinkler discharge conditions have been selected as a basis for the design of low-cost systems: 0.274-in. sprinkler operating at 8 psig and 6 gpm, and 0.137-in. sprinkler operating at 88.5 psig and 4.7 gpm. These two discharge conditions require smaller water discharge rates than that required by NFPA 13-D standards, but still provide adequate life-safety protection in fires of the kind studied in this program. Other sprinkler discharge conditions tested, for which reliable CO measurements were made, require more water than the recommended conditions.

TABLE V

CUMULATIVE CO CONCENTRATION (ppm-min)

Sprinkler Discharge Pressure Δp (psig)		Sprinkler Orifice Diameter, D (in.) 0.438	0.329	0.274	0.219	0.164	0.137	0.110
8.0	CO to t_f	4,650	4,370	6,720				
	CO to t_s	5,050	4,680	7,030				
	CO to t_s + 5 min.	6,420	6,200	8,830				
	CO to t_s + 10 min.	7,430	7,570	13,780				
	CO to t_s + 20 min.	8,980	9,870	27,080				
28.5	CO to t_f			4,120	4,830	—		
	CO to t_s			4,520	5,270	—		
	CO to t_s + 5 min.			7,550	6,480	—		
	CO to t_s + 10 min.			17,030	11,470	—		
	CO to t_s + 20 min.			39,780	28,920	—		
88.5	CO to t_f					4,780	5,820	—
	CO to t_s					5,100	6,080	—
	CO to t_s + 5 min					6,505	8,030	—
	CO to t_s + 10 min					8,080	13,720	—
	CO to t_s + 20 min					11,700	29,650	—

Note: t_f - time of flaming

t_s - time of sprinkler activation

TABLE VI

GAS TEMPERATURE AT EYE LEVEL (°F)

(4 ft 6 in. from floor, 3 ft from north wall)

Sprinkler Discharge Pressure Δp (psig)		Sprinkler Orifice Diamater, D (in.) 0.438	0.329	0.274	0.219	0.164	0.137	0.110
8.0	T_{ei}	70	75	84				
	T_e	150	144	147				
	T_e'	80	76	89				
28.5	T_{ei}			68	71	72		
	T_e			137	147	156		
	T_e'			81	85	85		
88.5	T_{ei}					74	76	79
	T_e					137	159	131
	T_e'					83	89	92

Note: T_{ei} - gas temperature at start of test

T_e - gas temperature at time of sprinkler activation

T_e' - gas temperature at 1 min after sprinkler activation

Although the "smokiness" in the sense of visibility is not judged to be a critical factor in the survivability of a sprinkler fire, the optical density is still of considerable interest. Table VII and Figures 16, 17, 18 present optical density at eye level. It is interesting to note that for the 0.438-in. and 0.329-in. sprinklers at 8 psig the optical densities eventually decreased after activation of the sprinkler.

6.2 PROPERTY PROTECTION

The ability of the sprinkler to provide property protection was evaluated by analyzing the ceiling temperature history over the source of the fire and the gas temperature behavior at several points near the ceiling in the fire room.

Table VIII shows the ceiling temperature (thermocouple C1) at a point directly above the ignition point. Temperatures at the time of sprinkler activation (the maximum ceiling temperature during the test) and 1 min. after sprinkler activation are presented for all nine sprinkler conditions. As is shown, peak ceiling temperatures reach between 250 and 350°F. The ratio $(T_c - T_c')/(T_c - T_{ci})$ where T_c = ceiling temperature at sprinkler activation, T_c' = ceiling temperature at 1 min. after sprinkler activation and T_{ci} = ceiling temperature at the start of the test, indicates the degree of cooling that is achieved in the 1 min. after sprinker activation. For all nine cases, the ceiling temperature was reduced below 220°F after 1 min. of sprinkler operation. Cellulosic and plastic materials usually start to pyrolyze vigorously around a temperature of 500°F[14]. Hence, the sprinkler protection was more than sufficient to prevent the fire spread to the building structure.

Table IX shows the average value of the four gas temperatures measured by the thermocouples L1, L4, L7 and L10 (see Figure 10) located 1 ft. below the living-room ceiling. Average gas temperatures are shown at the start of the test, at sprinkler activation and at 1 min. after sprinkler activation. For all tests, the maximum value was reached at sprinkler activation and ranged between 190 and 215°F. The cooling effect of the sprinkler is presented in the nondimensionalized form, $(\bar{T}_g' - \bar{T}_g'')/(\bar{T}_g' - \bar{T}_{gi})$ where $\bar{T}_g'$ = average gas temperature at sprinkler activation, $\bar{T}_g''$ = average gas temperature 1 min. after sprinkler activation and $\bar{T}_{gi}$ = average temperature at the start of the test. The

TABLE VII

OPTICAL DENSITY AT EYE LEVEL (ft^{-1})

Sprinkler Discharge Pressure Δp(psig)		Sprinkler Orifice Diameter D (in.)						
		0.438	0.329	0.274	0.219	0.164	0.137	0.110
	OD at t_f	0.44	0.27	0.30				
	OD at t_s	0.43	0.25	0.27				
8.0	OD at t_s + 5 min.	0.54	0.57	0.59				
	OD at t_s + 10 min.	0.41	0.48	-				
	OD at t_s + 20 min.	0.26	0.35	-				
	OD at t_f			0.32	0.27	0.20		
	OD at t_s			0.23	0.27	0.16		
28.5	OD at t_s + 5 min.			0.61	0.94	0.45		
	OD at t_s + 10 min.			0.60	0.54	0.75		
	OD at t_s + 20 min.			0.45	0.60	0.62		
	OD at t_f					0.44	0.20	0.07
	OD at t_s					0.35	0.16	0.10
88.5	OD at t_s + 5 min.					0.50	0.63	0.29
	OD at t_s + 10 min.					0.53	0.44	0.37
	OD at t_s + 20 min.					0.58	0.51	0.74

Note:

t_f - time of flaming

t_s - time of sprinkler activation

OD (ft^{-1}) = $\ell^{-1} \log_{10}(I_o/I)$

where ℓ is the optical path length (ft^{-1}), I_o and I are the photodetector output (linear with light intensity) in absence and presence of smoke, respectively.

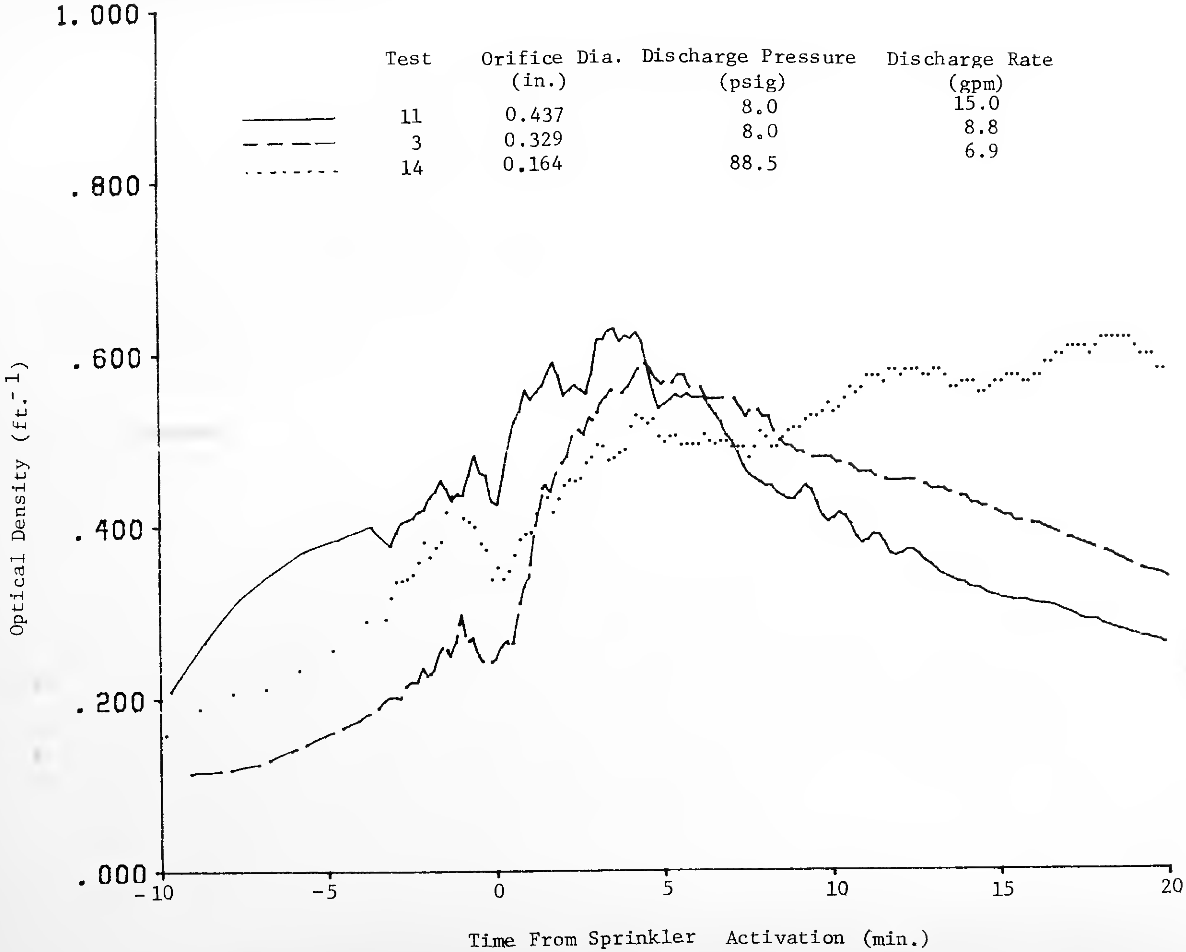


FIGURE 16 OPTICAL DENSITY AT EYE LEVEL IN LIVING ROOM FOR TESTS 3, 11, AND 14

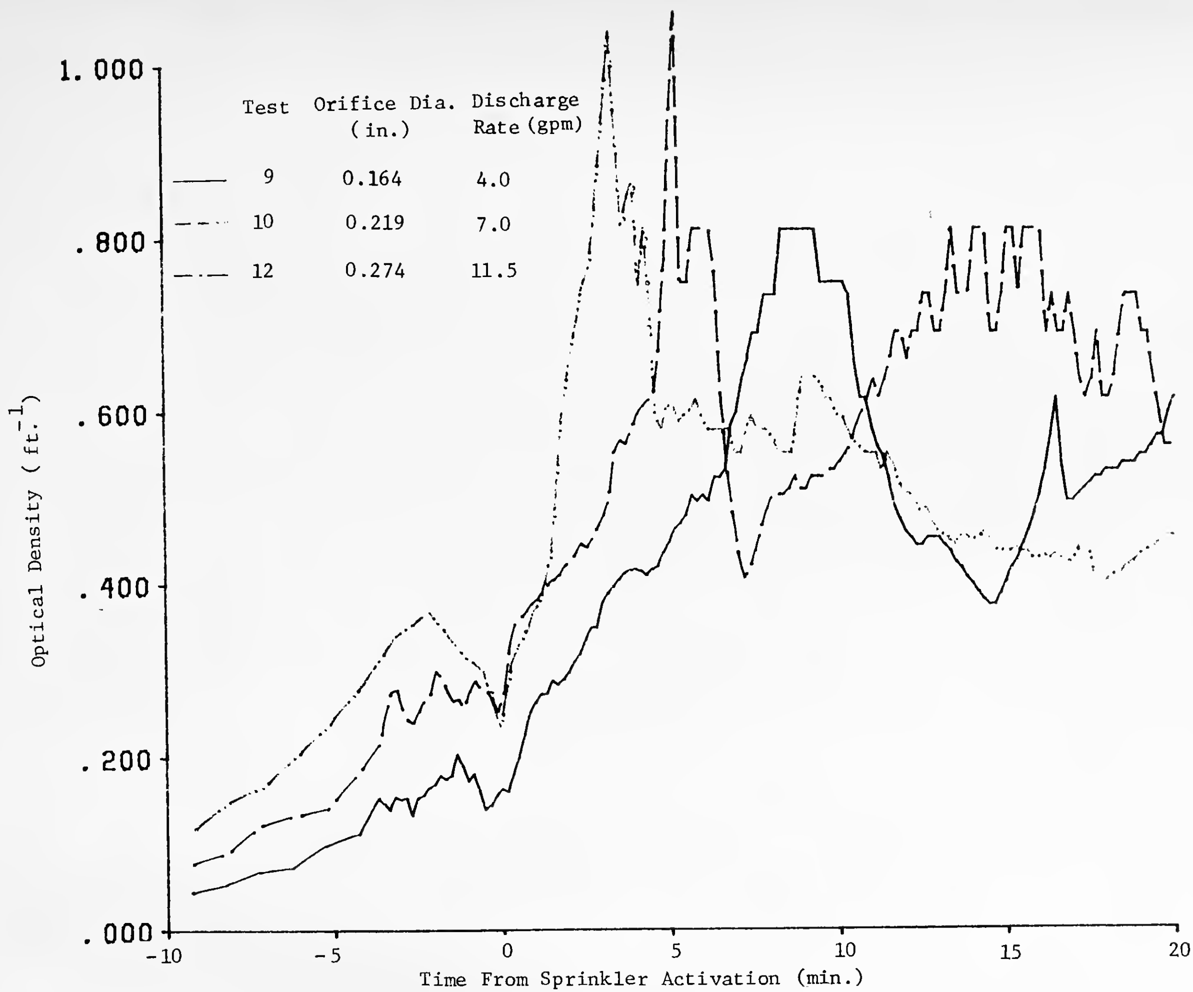


FIGURE 17 OPTICAL DENSITY AT EYE LEVEL IN LIVING ROOM FOR TESTS 9, 10, AND 12 (28.5 psig Discharge Pressure)

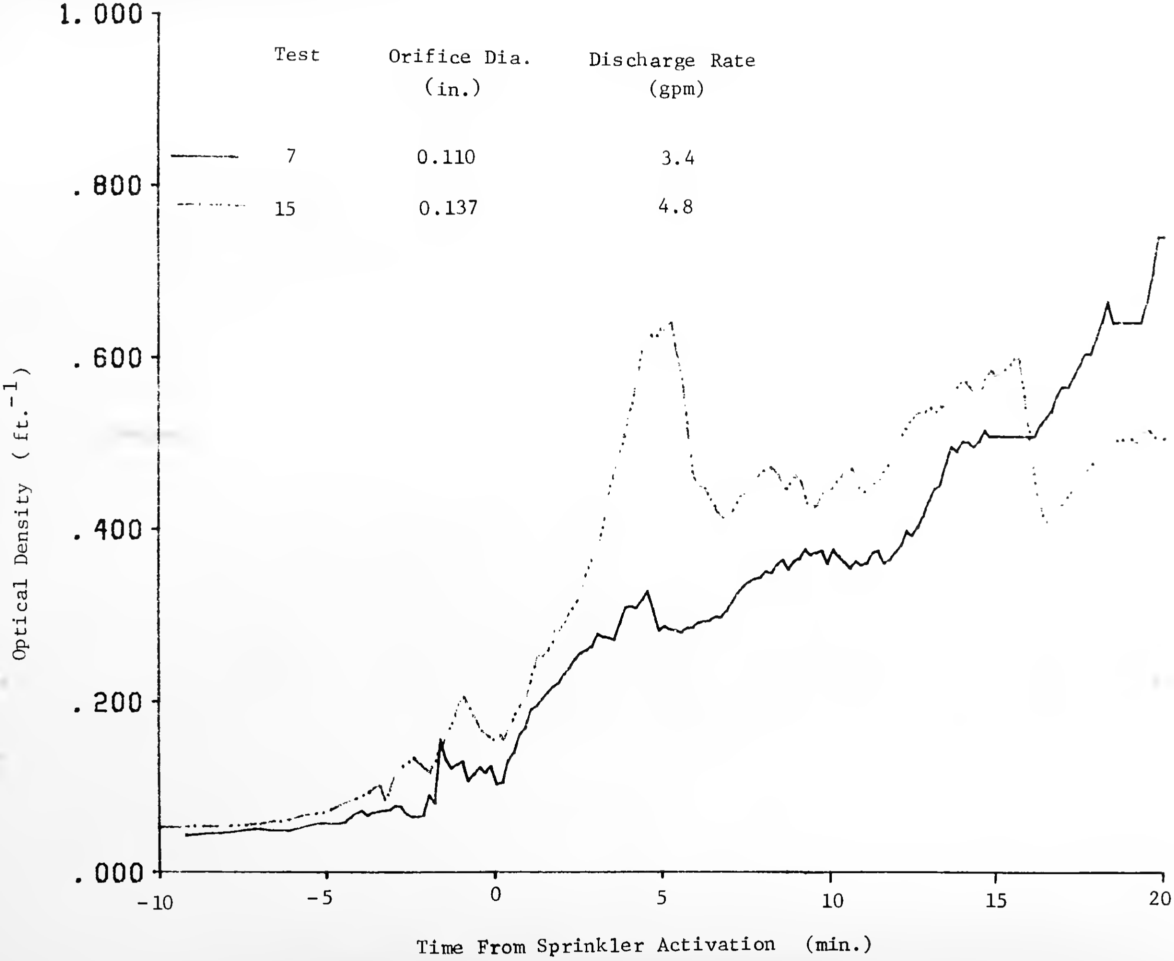


FIGURE 18 OPTICAL DENSITY AT EYE LEVEL IN LIVING ROOM FOR TESTS 7 AND 15 (88.5 psig Discharge Pressure)

TABLE VIII

CEILING TEMPERATURE DIRECTLY ABOVE THE IGNITION POINT (°F)

Sprinkler Discharge Pressure Δp(psig)		Sprinkler Orifice Diameter, D (in.)						
		0.438	0.329	0.274	0.219	0.164	0.137	0.110
8.0	T_c	283	333	306				
	T_c'	173	203	219				
	T_{ci}	70	72	84				
	$(T_c - T_c')/(T_c - T_{ci})$	0.52	0.50	0.39				
28.5	T_c			264	276	311		
	T_c'			172	224	216		
	T_{ci}			70	70	72		
	$(T_c - T_c')/(T_c - T_{ci})$			0.47	0.25	0.40		
88.5	T_c					265	337	262
	T_c'					186	208	209
	T_{ci}					77	79	84
	$(T_c - T_c')/(T_c - T_{ci})$					0.42	0.50	0.30

Note: T_{ci} - Ceiling temperature at start of test

T_c - Ceiling temperature at time of sprinkler activation

T_c' - Ceiling temperature at 1 min. after sprinkler activation

TABLE IX

AVERAGE GAS TEMPERATURE ONE FOOT BELOW CEILING (°F)

Sprinkler Discharge Pressure Δp(psig)		Sprinkler Orifice Diameter, D (in.) 0.438	0.329	0.274	0.219	0.164	0.137	0.110
	$\overline{T}_g'$	214	215	215				
	$\overline{T}_g''$	95	109	131				
8.0	$\overline{T}_{gi}$	75	82	90				
	$(\overline{T}_g' - \overline{T}_g'')/(\overline{T}_g' - \overline{T}_{gi})$	0.86	0.79	0.67				
	$\overline{T}_g'$			193	195	209		
	$\overline{T}_g''$			89	134	116		
28.5	$\overline{T}_{gi}$			75	78	78		
	$(\overline{T}_g' - \overline{T}_g'')/(\overline{T}_g' - \overline{T}_{gi})$			0.88	0.52	0.71		
	$\overline{T}_g'$					194	215	180
	$\overline{T}_g''$					88	96	106
88.5	$\overline{T}_{gi}$					79	81	81
	$(\overline{T}_g' - \overline{T}_g'')/(\overline{T}_g' - \overline{T}_{gi})$					0.92	0.89	0.74

Note: $\overline{T}_{gi}$ - Average gas temperature at start of test

$\overline{T}_g'$ - Average gas temperature at the time of sprinkler activation

$\overline{T}_g''$ - Average gas temperature at 1 min. after sprinkler activation

average gas temperature is rapidly reduced below 135°F for all of the tests within 1 min. from sprinkler activation.

Figures 19, 20 and 21 show the detailed measurement of the average gas temperature (T_g) from 5 min. before to 20 min. after sprinkler activation. Figure 19 pertains to a discharge pressure of 8-psig, while Figure 19 shows the 28.5-psig data, and Figure 20 the 88.5-psig data.

As can be seen in Figure 19, (0.438-in., 0.329-in. and 0.274-in. orifices - 8 psig discharge pressure) all three sprinklers quickly cool the room and maintain the temperature near the initial ambient temperature for the remainder of the test. Figure 20 (0.274-in., 0.219-in. and 0.164-in. orifices - 28.5 psig) the cooling is initially very rapid but for the 0.219-in. and 0.164-in. sprinklers the temperature begins to climb after a few minutes of sprinkler operation as a result of the fire spreading behind the bolster and under the mattress. The fire was brought under control later in the test for each of these cases. For the 0.110-in. sprinkler at 88.5 psig (Figure 21) the fire continued to grow slowly after spreading to the backs of the bolsters, however, the fire did not begin to grow until 10 min. after sprinkler activation (Figure 21) and the temperature near the ceiling reached only 200°F approximately at 20 min. after sprinkler activation.

For all cases, no damage was done to the room divider. Damage to areas other than the couch was limited to some scorching of the east wall behind the couch. Flames reached 3-4 ft. above the mattress at their peak. During sprinkler operation, flames were confined to the back, underside of the couch. If extra furnishings had been positioned near the couch it is unlikely that they would have ignited.

The sprinkler-link response time was in the range of 59 - 130 sec., depending on the gas velocity and temperature in the vicinity of the link. Table X lists sprinkler response times and gas temperatures and velocities near the link at selected times up to sprinkler activation; the Table also lists the maximum burning rate which occurred just prior to sprinkler activation.

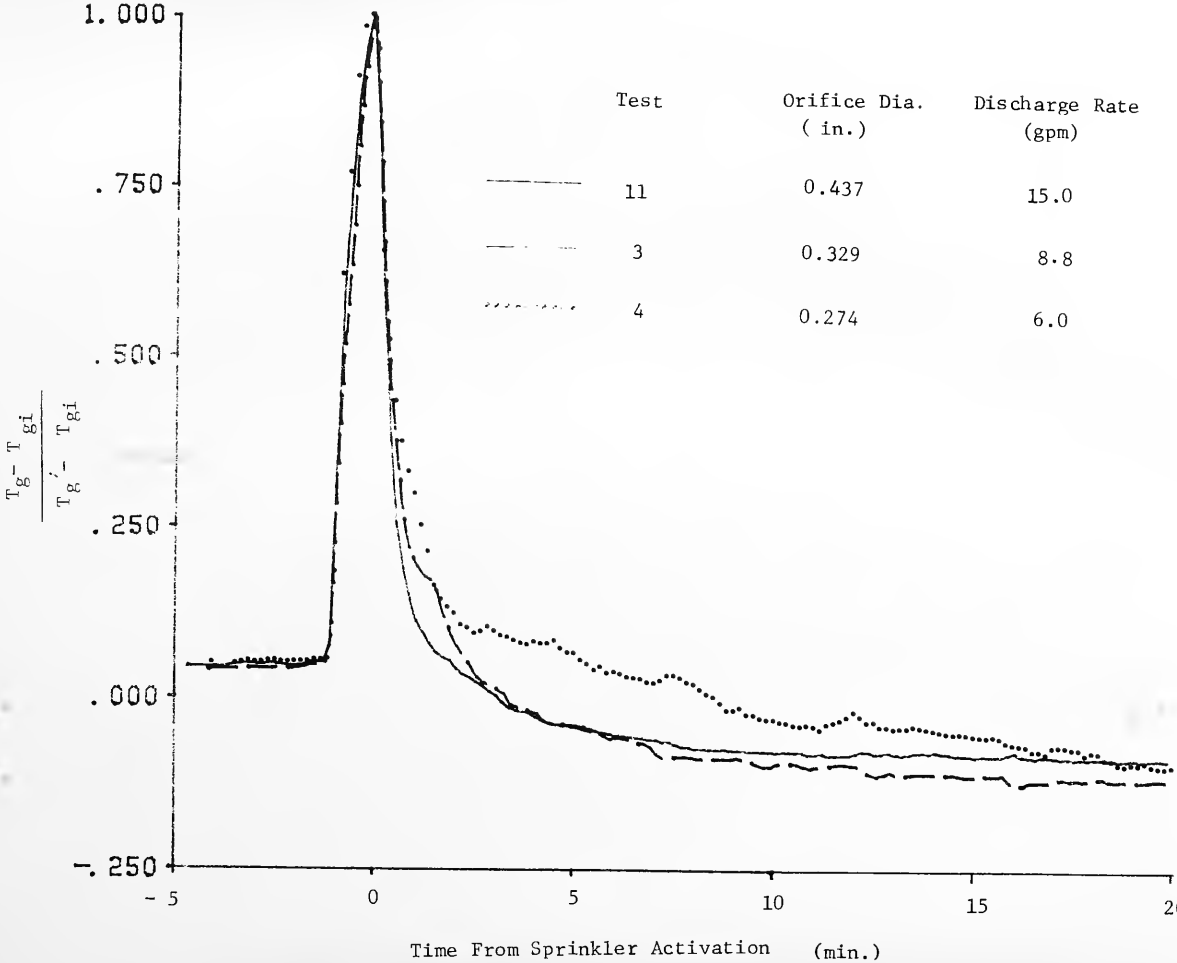


FIGURE 19 NON-DIMENSIONALIZED AVERAGE GAS TEMPERATURE ONE FOOT BELOW THE CEILING FOR TESTS 3, 4, AND 11 (8 psig Discharge Pressure)

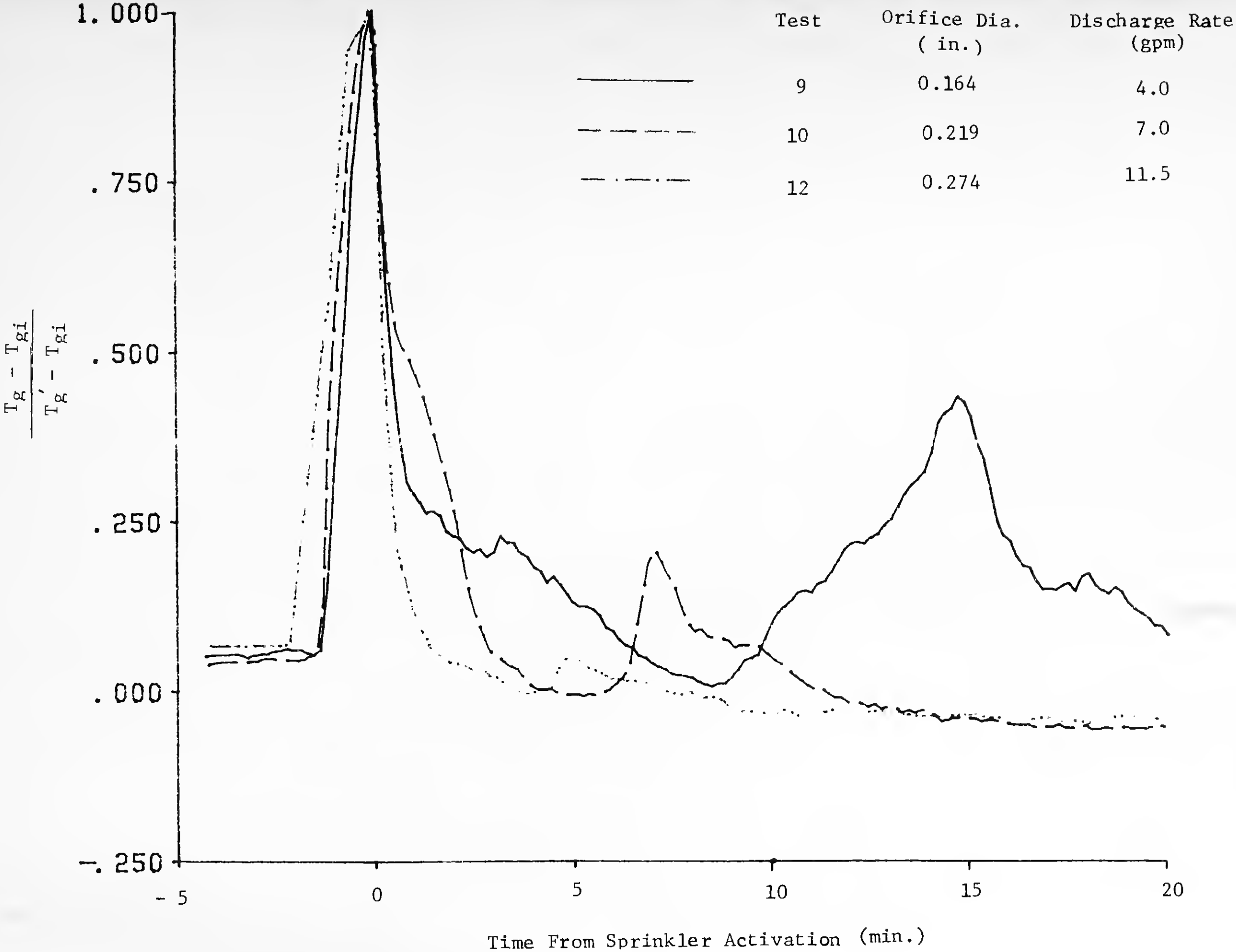


FIGURE 20 NON-DIMENSIONALIZED AVERAGE GAS TEMPERATURE ONE FOOT BELOW THE CEILING FOR TESTS 9, 10, AND 12 (28.5 psig Discharge Pressure)

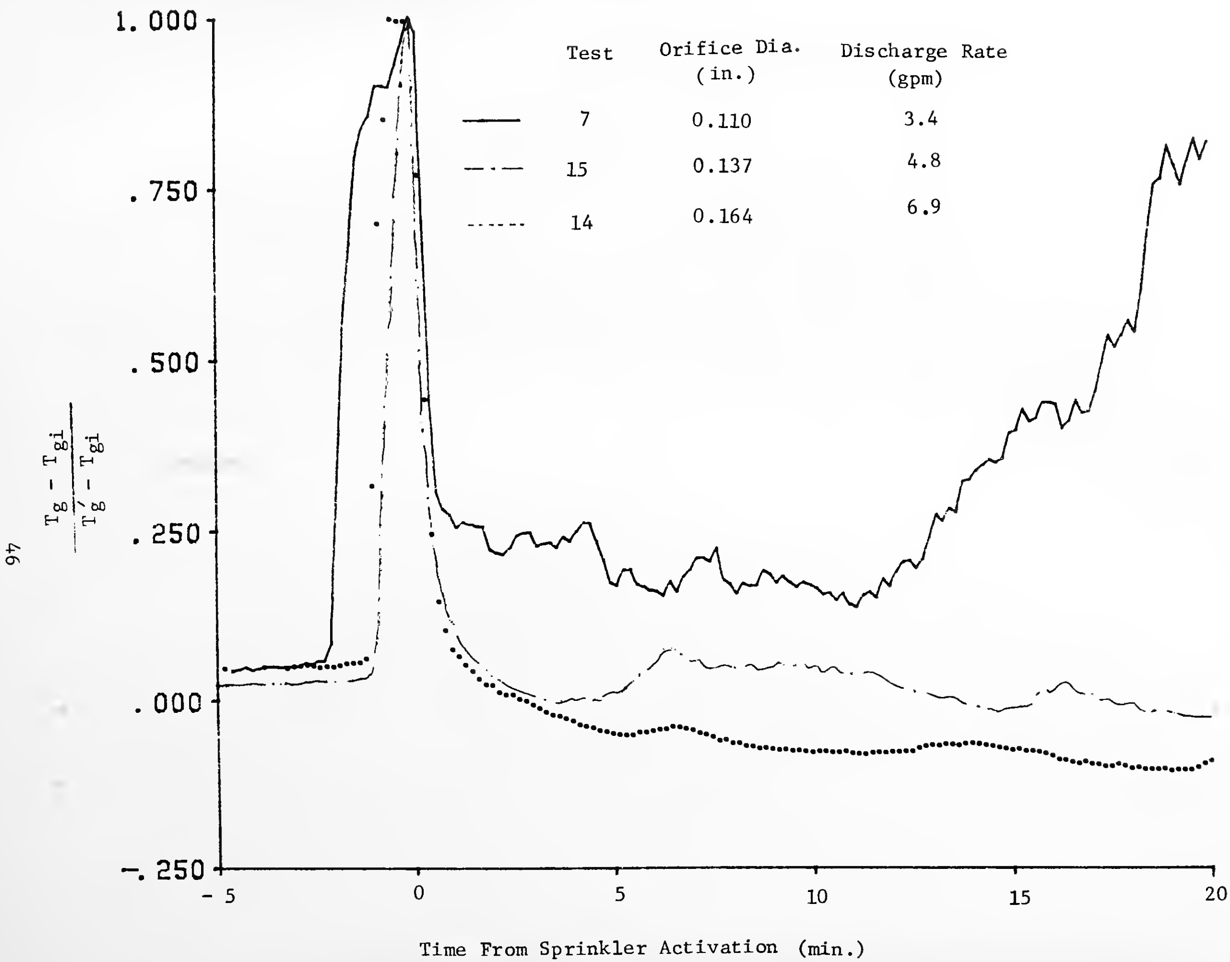


FIGURE 21 NON-DIMENSIONALIZED AVERAGE GAS TEMPERATURE ONE FOOT BELOW THE CEILING FOR TESTS 7, 14, AND 15 (88.5 psig Discharge Pressure)

TABLE X

SPRINKLER LINK RESPONSE TIME (sec)

Sprinkler Discharge Pressure Δp(psig)		Sprinkler Orifice Diameter D (in.) 0.438	0.329	0.274	0.219	0.164	0.137	0.110
	t_r	69	70	68				
	$\dot{m}_{B\ max}$	0.95	0.74	0.64				
	T_{gl} at t_f	109.2	91.2	103.3				
	T_{gl} at t_f+20sec	239.9	229.6	268.3				
8.0	T_{gl} at t_f+40sec	253.4	260.2	273.0				
	T_{gl} at t_s	262.4	285.8	257.0				
	V_{gl} at t_f	3.41	1.61	2.20				
	V_{gl} at t_f + 20sec	4.66	4.46	5.54				
	V_{gl} at t_f + 40sec	4.66	3.61	4.27				
	V_{gl} at t_s	5.48	4.99	4.20				
	t_r			96	86	82		
	$\dot{m}_{B\ max}$			0.82	0.58	0.61		
	T_{gl} at t_f			84.4	86.2	94.8		
	T_{gl} at t_f + 20 sec			176.0	206.4	199.9		
28.5	T_{gl} at t_f + 40 sec			210.2	219.4	232.2		
	T_{gl} at t_s			237.6	251.1	263.1		
	V_{gl} at t_f			0.89	1.08	2.13		
	V_{gl} at t_f + 20 sec			4.37	4.53	3.97		
	V_{gl} at t_f + 40 sec			4.05	3.45	3.84		
	V_{gl} at t_s			4.82	4.40	6.14		
	t_r					75	59	130
	$\dot{m}_{B\ max}$					0.58	0.82	0.39
	T_{gl} at t_f					95.7	88.7	108.5
	T_{gl} at t_f + 20 sec					254.7	236.7	203.0
88.5	T_{gl} at t_f + 40 sec					255.4	270.0	200.7
	T_{gl} at t_s					232.3	280.6	220.8
	V_{gl} at t_f					2.13	0.92	2.53
	V_{gl} at t_f + 20 sec					4.66	4.95	3.64
	V_{gl} at t_f + 40 sec					4.46	3.81	2.92
	V_{gl} at t_s					4.82	6.07	3.45

Note: 1) $t_r = = t_s - t_f$ - response of sprinkler link (sec)

2) t_f - time of flaming

3) t_s - time of sprinkler activation

4) $\dot{m}_{B\ max}$ - maximum burning rate (lbm/min)

5) T_{gl} - gas temperature near sprinkler link (°F)

6) V_{gl} - gas velocity near sprinkler link (ft/sec)

6.3 WATER DISTRIBUTION AND FIRE BEHAVIOR

At the end of the fire test series, water distributions of the nine sprinkler test conditions were measured. A group of 30 metal pans, 6 in. x 12 in. x 12 in. high, were placed in the same location in the living room as the couch to collect water over an area approximately the same size as the surface of the mattress. The pans were positioned so that the upper edge was at the same elevation as the surface of the mattress (19 in. above the floor). Water collected in each pan over a 20-min. period was measured in a graduated cylinder. The data from these tests are presented in Table XI(a-i). The number in each block represents the local water application density for each collection area.*

During each fire test the burn patch grew to a 1 to 1 1/2-ft. dia. semi-circle on the bolster and 1 1/2 to 2 ft. dia. semi-circle on the mattress at the time of flaming. In the freeburn period between flaming and sprinkler activation, the fire was generally confined to this area, burning deeper into the urethane foam of the mattress and bolster as the fire progressed. Hence, the water application density on the perimeter of this area was important in containing the fire spread. In Table XI(a-i), a dotted line has been drawn to roughly represent the extent of the burn patch prior to sprinkler activation. The nine pans in the northeast corner of the collection area have been labeled. The water applied to Regions 3, 6, 8 and 9 was essential to prevent the fire spread underneath the mattress.

Figures 22(a-i) show the post-test undersurface of the mattress; and Figures 23(a-i) show the post-test appearance** of the couch for the nine different sprinkler discharge combinations.

For the 0.438-in. sprinkler at 8 psig, the application density in Regions 1-9 was quite high (0.034 - 0.105 gpm/ft^2); Table XI,a. The fire was extinguished rapidly. Damage was limited to a burn patch of 1 1/2-ft. dia. semi-circle on the bolster and 3-ft. dia. semi-circle on the couch as shown in Figures 22a and 23a. For the 0.164-in. sprinkler at 88.5 psig, damage was

* The pans are each 6 in. x 12 in. inside dimension with 1/8-in. walls so that when 30 are positioned in five rows of six pans each, the total area covered is 73 1/2 in. x 31 1/4 in. which is slightly less than the 75 in. x 33 in. actual surface area of the mattress. The collection area for each pan was considered to be 6.25 in. x 12.25 in.: 0.53 ft^2.

**Some of the photographs were taken inside the living room, while the rest were taken after the couches moved outside.

TABLE XI

LOCAL WATER APPLICATION DENSITIES (gpm/ft^2)

(Top Row Corresponds to Back of Mattress)

a) Sprinkler Scale = 1
Orifice Diameter = 0.438 in.
Discharge Pressure = 8.0 psig
Flow Rate = 15 gpm

[1] 0.034	[2] 0.092	[3] 0.105	0.124	0.095	0.105
[4] 0.097	[5] 0.089	[6] 0.055	0.051	0.087	0.095
[7] 0.088	[8] 0.105	[9] 0.057	0.044	0.097	0.096
0.072	0.102	0.056	0.037	0.088	0.073
0.055	0.070	0.053	0.030	0.071	0.051

b) Sprinkler Scale = 3/4
Orifice Diameter = 0.329 in.
Discharge Pressure = 8.0 psig
Flow Rate = 8.8 gpm

[1] 0.084	[2] 0.066	[3] 0.086	0.077	0.065	0.074
[4] 0.055	[5] 0.040	[6] 0.042	0.040	0.038	0.044
[7] 0.041	[8] 0.032	[9] 0.032	0.037	0.031	0.037
0.038	0.027	0.024	0.032	0.028	0.030
0.038	0.028	0.019	0.027	0.025	0.025

c) Sprinkler Scale = 5/8
Orifice Diameter = 0.274 in.
Discharge Pressure = 8.0 psig
Flow Rate = 6.0 gpm

[1] 0.052	[2] 0.051	[3] 0.061	0.069	0.055	0.042
[4] 0.041	[5] 0.032	[6] 0.036	0.037	0.040	0.033
[7] 0.034	[8] 0.027	[9] 0.030	0.029	0.034	0.030
0.029	0.024	0.025	0.025	0.030	0.025
0.026	0.022	0.021	0.023	0.026	0.022

d) Sprinkler Scale = 5/8
Orifice Diameter = 0.274 in.
Discharge Pressure = 28.5 psig
Flow Rate = 11.5 gpm

[1] 0.089	[2] 0.159	[3] 0.155	0.135	0.124	0.133
[4] 0.032	[5] 0.038	[6] 0.047	0.046	0.045	0.040
[7] 0.029	[8] 0.026	[9] 0.028	0.027	0.033	0.027
0.032	0.023	0.023	0.024	0.028	0.024
0.034	0.023	0.019	0.024	0.027	0.026

e) Sprinkler Scale = 1/2
Orifice Diameter = 0.219 in.
Discharge Pressure = 28.5 psig
Flow Rate = 7.0 gpm

[1] 0.061	[2] 0.087	[3] 0.063	0.056	0.062	0.050
[4] 0.025	[5] 0.029	[6] 0.027	0.027	0.036	0.030
[7] 0.023	[8] 0.024	[9] 0.023	0.024	0.031	0.027
0.024	0.023	0.020	0.020	0.026	0.025
0.023	0.023	0.018	0.018	0.020	0.023

f) Sprinkler Scale = 3/8
Orifice Diameter = 0.164 in.
Discharge Pressure = 28.5 psig
Flow Rate = 3.9 gpm

[1] 0.011	[2] 0.008	[3] 0.006	0.010	0.0053	0.0067
[4] 0.013	[5] 0.011	[6] 0.0079	0.011	0.0063	0.011
[7] 0.015	[8] 0.016	[9] 0.010	0.012	0.0081	0.017
0.015	0.023	0.014	0.013	0.012	0.023
0.014	0.030	0.018	0.014	0.020	0.032

g) Sprinkler Scale = 3/8
Orifice Diameter = 0.164 in.
Discharge Pressure = 88.5 psig
Flow Rate = 6.8 gpm

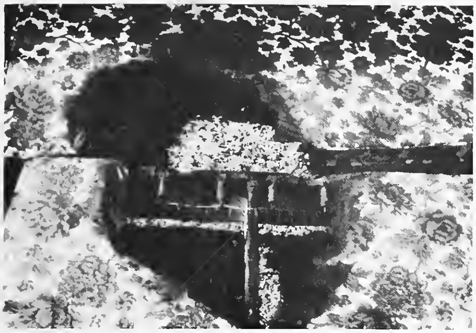
[1] 0.024	[2] 0.054	[3] 0.053	0.044	0.041	0.015
[4] 0.018	[5] 0.039	[6] 0.050	0.054	0.047	0.017
[7] 0.020	[8] 0.033	[9] 0.042	0.054	0.047	0.019
0.028	0.031	0.033	0.045	0.041	0.023
0.039	0.033	0.029	0.036	0.034	0.028

h) Sprinkler Scale = 5/16
Orifice Diameter = 0.137 in.
Discharge Pressure = 88.5 psig
Flow Rate = 4.7 gpm

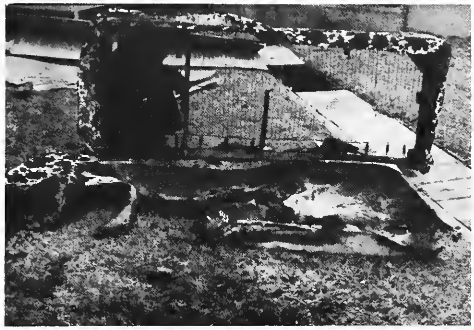
[1] 0.0055	[2] 0.013	[3] 0.015	0.013	0.012	0.011
[4] 0.009	[5] 0.017	[6] 0.018	0.015	0.019	0.017
[7] 0.014	[8] 0.025	[9] 0.025	0.020	0.031	0.027
0.020	0.034	0.032	0.029	0.045	0.041
0.029	0.045	0.047	0.041	0.067	0.068

i) Sprinkler Scale = 1/4
Orifice Diameter = 0.110 in.
Discharge Pressure = 88.5 psig
Flow Rate = 3.4 gpm

[1] 0.00083	[2] 0.00099	[3] 0.0019	0.0023	0.0010	0.00066
[4] 0.0016	[5] 0.0021	[6] 0.0037	0.0040	0.0023	0.0016
[7] 0.0027	[8] 0.0048	[9] 0.0074	0.0067	0.0053	0.0040
0.0035	0.0099	0.014	0.011	0.010	0.0093
0.0054	0.012	0.023	0.018	0.019	0.015



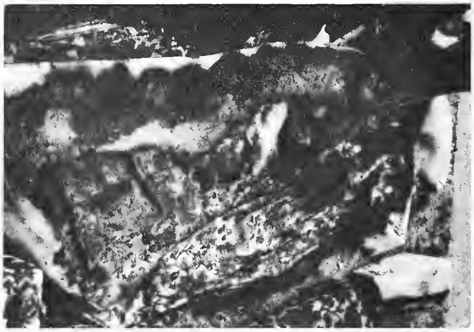
a) Test 11 - 0.438-in sprinkler
at 8 psig



b) Test 3 - 0.329-in. sprinkler
at 8 psig

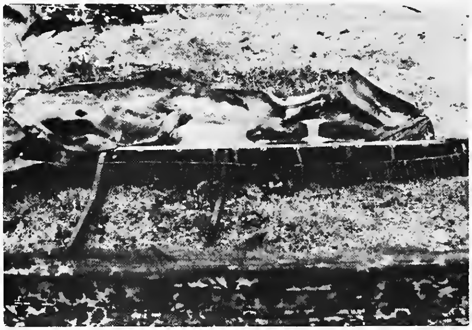
c) Test 4 - 0.274-in. sprinkler
at 8 psig

FIGURE 22 POST-TEST APPEARANCE OF UNDER SURFACE OF MATTRESS



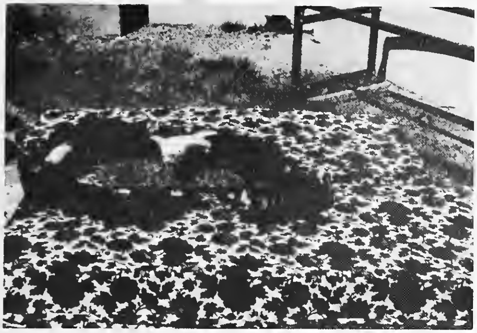
d) Test 12 - 0.274-in. sprinkler
at 28.5 psig

e) Test 10 - 0.219-in. sprinkler
at 28.5 psig



f) Test 9 - 0.164-in. sprinkler
at 28.5 psig

FIGURE 22 (Continued)

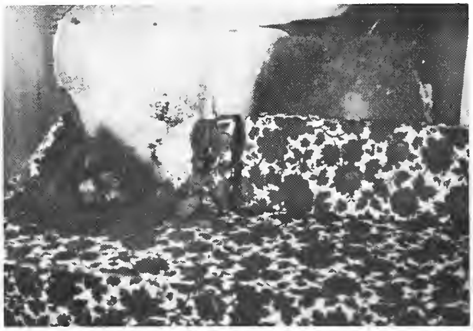


g) Test 14 - 0.164-in. sprinkler at 88.5 psig

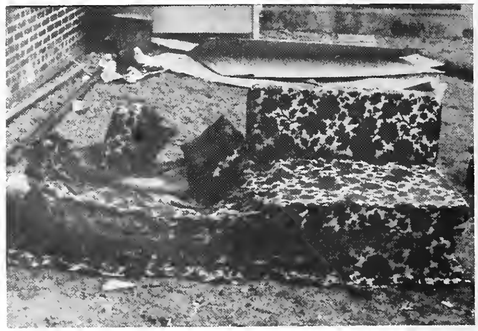
h) Test 15 - 0.137-in sprinkler at 88.5 psig

i) Test 7 - 0.110-in. sprinkler at 88.5 psig

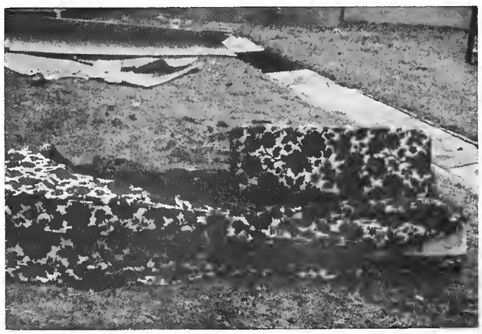
FIGURE 22 (Continued)



a) Test 11 - 0.438-in. sprinkler
at 8 psig

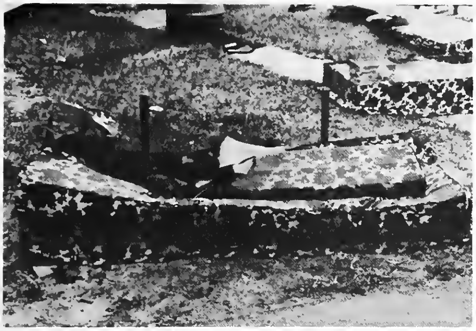


b) Test 3 - 0.329-in. sprinkler
at 8 psig

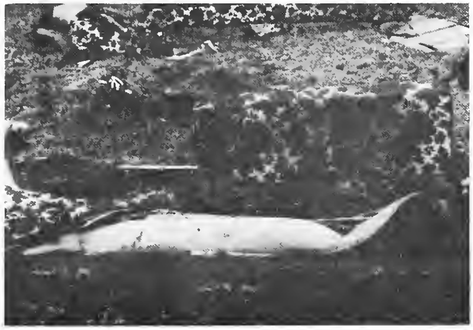


c) Test 4 - 0.274-in. sprinkler
at 8 psig

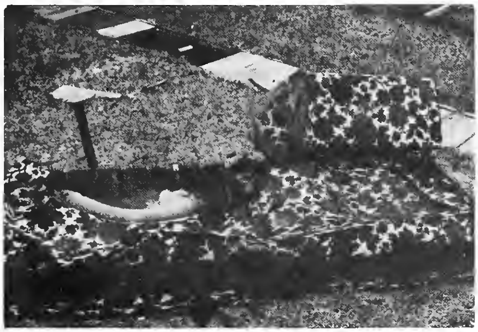
FIGURE 23 POST-TEST APPEARANCE OF COUCH



d) Test 12 - 0.274-in. sprinkler at 28.5 psig



e) Test 10 - 0.219-in. sprinkler at 28.5 psig



f) Test 9 - 0.164-in. sprinkler at 28.5 psig

FIGURE 23 (Continued)

g) Test 14 - 0.164-in. sprinkler at 88.5 psig

h) Test 15 - 0.137-in sprinkler at 88.5 psig

i) Test 7 - 0.110-in. sprinkler at 88.5 psig

FIGURE 23 (Continued)

confined to the left bolster and two semi-circles (3-ft. dia. and 1-ft. dia.) on the couch (Figures 22g. and 23g.); the minimum application density in Regions 3, 6, 8 and 9 was 0.033 gpm/$ft.^2$ (Table XI g.).

For slightly reduced densities in Regions 8 and 9 of the sprinkler discharge condition (0.329-in. sprinkler at 8 psig (Table XI b)), the fire spread underneath the mattress, approximately down 3/4 of the length of the couch (Figures 22 b and 23 b). This suggests a critical application density near 0.033 gpm/$ft.^2$ for halting fire spread underneath the mattress in the test fires. As soon as the fire spread was stopped, CO generation ceased. It is recalled (Section 6.1)that for these three discharge conditions (0.438-in. and 0.329-in. sprinklers at 8 psig and 0.164-in. sprinkler at 88.5 psig), the CO concentrations were maintained below 450 ppm during the entire test period (Figure 14).

For other test combinations, the application densities in Regions 3, 6, 8 and 9 were below 0.033 gpm/$ft.^2$ (Table XI, c-f,h,i), and more extended fire spread underneath the mattress is evident from Figures 22 c-f,h,i and 23 c-f, h,i. The CO concentration at eye level increased during sprinkler operation (Figure 15). However, the rate of fire spread was sufficiently controlled by the sprinkler in the tests with reliable CO measurements; i.e., the gas temperature and CO concentration were kept low enough to maintain a survivable environment for 20 min.following sprinkler operation.

VII
CONCLUSIONS

Sprinklers have been shown capable of providing life-safety and property protection in a common fire scenario leading to fire deaths in the home. Furthermore, water discharge rates considerably below those provided by NFPA 13-D have been shown to be adequate.

The fire scenario simulated in the experimental program was a cigarette dropped into the crevice of a couch in the living room, with subsequent initiation of smoldering and eventual transition to flaming. Typically, transition to flaming occurred after a smoldering interval of 60 min. Generation of smoke and CO became vigorous only in the final 15 min. before flaming; however, CO concentrations before flaming never exceeded 360 ppm at eye level. Up to flaming, the environment was deemed survivable.

A total of nine combinations of sprinkler size and water discharge were investigated. Survivability was judged from CO concentrations and temperatures measured at eye level in the living room for a time period extending to 20 min. past sprinkler activation. Structural (property) protection was judged from gas temperatures under the ceiling and surface temperatures in the ceiling. All test combinations of sprinkler size and water pressure provided more than adequate structural protection. Some test combinations also provided adequate life-safety protection on the basis of the adopted survival criteria.

The water density distribution of a sprinkler has been identified as an important factor in controlling the generation rate of CO.

One low-pressure and one high-pressure combination were selected for future consideration in low-cost systems, both providing conservatively adequate life-safety and property protection in the test fires: a 0.274-in. sprinkler at 8 psig (6 gpm) and a 0.137-in. sprinkler at 88.5 psig (4.7 gpm). The former sprinkler discharges water at a density which is 40 percent of the NFPA 13-D standard.

VIII

FUTURE WORK

For the remainder of the program, emphasis will be placed in two areas:

1. Optimization of the sprinkler design to further reduce the water demand and cost of residential sprinkler systems; and

2. Development of a standard fire test procedure for evaluating the performance of sprinklers developed in response to needs of low-cost, residential sprinkler systems.

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